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# REPORT ON THE STATUS OF PROJECT AMOS

(ACOUSTIC, METEOROLOGICAL, and OCEANOGRAPHIC SURVEY)

(1 January 1953-31 December 1954)

H. Wyser Marsh, Jr.

Morris Schulkin

USL RESEARCH REPORT NO. 255

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U. S. Navy Underwater Sound Laboratory

Fort Trumbull, New London, Conn.

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## SUMMARY PAGE

### THE PROBLEM

The problem consisted of obtaining sound-transmission data in the Atlantic Ocean and adjacent areas and correlating this information with meteorological and oceanographic conditions. The studies made involved ranges and frequencies of immediate interest in echo-ranging and passive-detection problems and contributed to the improvement of detection techniques, performance prediction, and system development. The approach to this problem was to provide shipboard instrumentation and modification for acoustic measurements at sea, carry out measurements, analyze and report on results obtained, and conduct operational and engineering research as required.

### FINDINGS

Ten joint acoustic-oceanographic cruises in the North Atlantic were completed through 1953. During these cruises, nearly 200 acoustic stations were occupied. All transmission data have been reduced and filed on IBM cards, and copies of most of these cards have been furnished to the Naval Research Laboratory and the University of Michigan. All North Atlantic and Mediterranean BT observations in the Woods Hole Oceanographic Institution File through November 1951 have been reduced to IBM cards and tabulated. Copies of the tabulations have been furnished to the Woods Hole Oceanographic Institution, the Navy Hydrographic Office, and the Agricultural and Mechanical College of Texas. The Hydrographic Office has agreed to keep this basic file up to date. The transmission data cover a frequency range from 70 cps to 25 kc, and vertical reverberation measurements cover the range from 2.2 to 34 kc.

An analysis of AMOS transmission data in the 2- to 25-kc frequency region, including the bottom mode of propagation, has been completed. Contours of transmission loss have been plotted for ten frequencies and three projector depths, for a standard temperature (50° F.) and a standard layer depth (100 ft). Correction charts have been plotted for each frequency for the correction required because of changes in layer depth, temperature, and sea state. Values for the absorption coefficient for various temperatures are also included. The AMOS propagation analysis was used to construct lateral range curves for hull-mounted, echo-ranging sonars at various frequencies and figures of merit for submarines at periscope depth and at the best depth for avoiding detection. The curves also apply to specific layer depths and surface temperatures. Such curves were used by CAPT S. D. B. Merrill to space the ships of his screen in AsDevEx-I. A subsequent study of AsDevEx-I and other available data showed that the predicted and measured range performance compared favorably at all frequencies over a range of propagation conditions.

A theory has been developed for computing acoustic wave field intensities at all points including caustics and forced by phase corrections to the ray theory. Predictions of intensities in focusing regions by this method have been successful.

### RECOMMENDATIONS

As a result of the accomplishments of Project AMOS, it is recommended that the following actions be taken:

- a. Apply AMOS data to variable-depth sonar applications.
- b. Reduce and analyze AMOS deep-water propagation data at lower frequencies.
- c. Make extensive theoretical computations of acoustic fields.
- d. Prepare a sonar range prediction manual to replace NAVSHIPS 900,111.

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REPORT ON THE STATUS OF PROJECT AMOS  
(Acoustic, Meteorological, and Oceanographic Survey)  
(1 January 1953 - 31 December 1954).

by  
H. Wyson Marsh, Jr.

Morris Schulkin

USL RESEARCH REPORT, NO. 255

NE-120221-9

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## ABSTRACT

The Project AMOS work which was carried out through the period 1 January 1953 - 31 December 1954 is summarized. This is a final report of the AMOS deep-water acoustic measurements which began in June 1949. During the period covered by this report, the Underwater Sound Laboratory carried out a number of studies and analyses of AMOS data; these are included herein as Studies A through J.

The major study is an analysis of sound transmission at frequencies between 2 and 25 kc based on all the AMOS data and on other data available in the classified and nonclassified literature. Propagation-loss prediction charts based on this analysis are presented as a function of certain environmental parameters. An error study of the propagation analysis is presented next. The AMOS propagation analysis then is used to construct lateral range curves for hull-mounted, echo-ranging sonars at various frequencies and various figures of merit for submarines at periscope depth and at the depth which is best for avoiding detection. A comparison is made of measured and predicted ranges for a number of sonar systems. Studies of AMOS low-frequency noisemaker data analysis, ray tracing in the ocean, and bottom reflection in deep water are also presented, and a summary of Cruise TWELVE, which was completed early in this period, is included.

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## ADMINISTRATIVE INFORMATION

A hydrographic survey of vital sea lines was established in October 1948 by the Chief of Naval Operations. Authority for the survey was contained in CNO letter ser. 00159P31, 19 October 1948 (SECRET). The following month the Chief of Naval Operations, in CNO letter ser. 0503P414, 16 November 1948 (CONFIDENTIAL), requested the Bureau of Ships to initiate a program of acoustic measurements as a part of the hydrographic survey. In April 1949 the Underwater Sound Laboratory was directed to conduct sound transmission studies on board the hydrographic survey vessels AVP-30 and AVP-50 and to correlate the data obtained with oceanographic data concurrently taken. This assignment was made in BuShips letter ser. 241 (942A), 25 April 1949 (UNCLASSIFIED). Shortly thereafter, the unclassified code name "AMOS" was assigned to the Acoustical, Meteorological, and Oceanographic Survey program by authority of CNO letter ser. 0239P31, 26 May 1949 (CONFIDENTIAL).

The Navy index number for this program is NE-120221-9, and the Operational Requirement number is IO-15401. The work conducted by the Underwater Sound Laboratory was done under USL problem number D1A1. The measurements phase of the AMOS program has been completed; the analysis phase is continuing.

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## REPORT ON THE STATUS OF PROJECT AMOS (Acoustic, Meteorological, and Oceanographic Survey) (1 January 1953 - 31 December 1954)

### INTRODUCTION

Project AMOS (Acoustic, Meteorological, and Oceanographic Survey) was established in order to permit the collection of acoustic propagation data and the simultaneous observation of meteorological and oceanographic factors of significance to sonar performance in the vital sea lanes of the Atlantic Ocean during all seasons of the year. The information obtained was designed to cover both current and planned echo-ranging and listening frequencies.

The major objectives of Project AMOS have been achieved in one form or another. It is planned to make continued use of the Project AMOS propagation-loss data and environmental statistics for operational studies as indicated. The AMOS objectives are the following:

a. The preparation of a set of prediction charts for operational planning purposes. Such charts represent the sonar situation on a probability basis for each area of interest and for each month of the year. Various sets of charts corresponding to equipment categories, such as surface-ship-mounted echo-ranging sonar, variable-depth echo-ranging sonar, or submarine-installed low-frequency passive sonar, may be prepared. From these charts, it will be possible to determine not only the probability of achieving a particular detection range on a submarine by echo-ranging or listening but also the probable range of detection of a convoy by an enemy submarine.

b. The compilation of a set of detailed prediction charts for tactical employment, based upon the propagation loss and figure of merit for particular sonar equipments in relation to the prevailing oceanographic conditions. These charts will be used for day-to-day operations, for convoy screen spacing, and for similar applications.

c. The formulation of a set of design charts which will make possible intelligent design of sonar equipment to meet specified operational requirements.

The participants in the AMOS program were the U. S. Navy Hydrographic Office and the U. S. Navy Underwater Sound Laboratory. Jointly they were responsible for acquiring simultaneous acoustic and environmental data. The Underwater Sound Laboratory was responsible for the design, installation, and operation of acoustic equipment, while the Hydrographic Office carried out the design, installation, and operation of oceanographic and meteorological equipment. These agencies were also jointly responsible for the development of methods and techniques for field utilization and for presentation of the acoustic-oceanographic data to the Forces Afloat. This responsibility involved the preparation and publication of material which provides procedures for converting equipment characteristics and local environmental conditions into operationally and tactically usable terms.

In addition to acquiring acoustic data, the Laboratory undertook the analysis and correlation of simultaneously observed acoustic and environmental data for operational purposes. The Hydrographic Office was responsible for the acquisition and analysis of extensive environmental data for operational purposes and for the publication of operational sonar charts. It also was responsible for the preliminary planning of AMOS cruises, handled such matters as itineraries, project coordination, time and space allotments, personnel assignments, proposed shipyard installation of scientific equipment, and the preparation of technical instructions, and initiated "working-level" conferences with the agencies and vessels involved.

### SUMMARY OF ACCOMPLISHMENTS OF PROJECT AMOS

This report is a final report of the AMOS acoustic-environmental correlations in deep water. The

Underwater Sound Laboratory is now undertaking an extensive program of shallow-water propagation

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measurements.<sup>1</sup> A summary of the accomplishments of Project AMOS at the Underwater Sound Laboratory is now included.

Since the inception of the AMOS program, a sizable amount of acoustic propagation data has been accumulated for the North Atlantic Ocean for a wide range of acoustic frequencies and environmental conditions. The map in Fig. 1 shows the ten joint oceanographic and acoustic stations for which propagation-loss data have been obtained up through Cruise TWELVE. The AMOS cruises in which the Laboratory participated are listed below:

AMOS Cruises		
AMOS Cruise Number	Cruise Date	Acoustic Stations Occupied
TWO	June 1949	6
THREE	July-September 1949	29
FOUR	October-December 1949	17
FIVE	February-May 1950	25
SEVEN	November-December 1950	7
EIGHT	February-April 1951	30
NINE	June-September 1951	20
TEN	January-April 1952	18
ELEVEN	June-September 1952	20
TWELVE	February-April 1953	20
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The propagation-loss data obtained on these cruises were punched on IBM cards as indicated below. Finally a set of 26,672 IBM cards was prepared for all AMOS cruises with four-frequency (2.2, 3, 16, and 25 kc) propagation-loss data at standard projector depths, receiver depths, and ranges. Copies of most of these cards have been furnished to the Naval Research Laboratory and the University of Michigan. Available transmission data cover a frequency range of from 70 cps to 25 kc, and vertical reverberation measurements cover the range from 2.2 to 34 kc. A list of propagation-run station positions is given in Tables 1A and 1B for both high-frequency and low-frequency runs.

All North Atlantic and Mediterranean BT observations in the Woods Hole Oceanographic Institution File through November 1951 have been re-

<sup>1</sup> The present status of the shallow-water measurements program is covered in USL Report No. 260, *Quarterly Report, 1 July - 30 September 1954* (CONFIDENTIAL).

duced to IBM cards and tabulated.<sup>2</sup> Copies of the tabulations have been furnished to the Woods Hole Oceanographic Institution, the Navy Hydrographic Office, and the Agricultural and Mechanical College of Texas. There are 131,000 pairs of cards in the North Atlantic File and 14,550 pairs of cards in the Mediterranean File. This set of environmental data cards has proved to be quite important in a number of applications. The cards have been separated into various geographical areas, and statistical compilations of important factors have been made. The Hydrographic Office has agreed to keep this basic file up to date and recently shipped 48,000 cards to the Laboratory.

Acoustic propagation and associated environmental data obtained from AMOS cruises are inventoried below.

AMOS Acoustic Cards		AMOS BT Card File	
(Card Layout Form, Fig. 7, USL Report No. 147)		(Card Layout Form, Fig. 8, USL Report No. 147)	
Cruise	No. of Cards	Cruise	No. of Cards
2	750	2	50
3	4,750	3	250
5	3,000	5	350
7	500	7	50
8	15,000	8	400
9	13,050	9	400
10	16,000	10	450
11	22,000	11	550
12	12,500	12	250
Total	88,050		2,750

Hydrographic Office AMOS Cruise Oceanographic Station File  
(Data for all cruises have been received in listing form.)  
(Card Layout Forms, Figs. 14-15, USL Report No. 147)

Cruise	No. of Cards
1	5100
2	650
3	2700
4	2400
5	2250

<sup>2</sup> The IBM cards used for this purpose are shown in Fig. 1 of USL Report No. 147, *Report on the Status of Project AMOS (20 April - 31 December 1951)*, by H. W. Marsh, Jr., and M. Schulkin, 19 February 1952 (CONFIDENTIAL).

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Table 1

## PROJECT AMOS PROPAGATION RUN STATIONS IN DEEP WATER

A. High Frequency [2.2, 8, 16, 25 (21, 29) kc]

Cruise	Acomatic Station	Date (start)	Latitude	Longitude	Water Depth (fm)	Hydrographic Station No.
2	1	18 VI 49	39°42'N	70°34'W	1340	53-1
	2	19 VI 49	38°17'N	69°25'W	1900	53-2
	3	19 VI 49	36°53'N	68°17'W	2530	53-3
	4	22 VI 49	36°53'N	62°05'W	2500	53-5
	5	22 VI 49	36°53'N	55°55'W	2800	53-6
	7	26 VI 49	43°12'N	60°00'W	890	52-9
3	3	16 VII 49	30°33'N	59°56'W	2800	53-2
	6	17 VII 49	30°13.5'N	54°28'W	2960	54-3
	9	18 VII 49	30°33'N	48°55'W	2620	53-5
	12	20 VII 49	30°51.3'N	43°17.5'W	1720	54-6
	15	21 VII 49	31°07'N	37°42'W	1850	53-8
	18	22 VII 49	31°24'N	32°04.8'W	2400	54-9
	21	23 VII 49	31°37.1'N	26°30.2'W	2825	53-11
	24	25 VII 49	31°57.5'N	20°49.0'W	2600	54-12
	27	26 VII 49	32°13.4'N	15°26.0'W	2340	53-14
	32	28 VII 49	34°24.2'N	7°35.2'W	710	54-16
	36	31 VII 49	36°05.0'N	9°43.1'W	2170	54-19
	39	1 VIII 49	38°23'N	10°25.5'W	2650	53-19
	42	8 VIII 49	40°49.5'N	13°49.5'W	2800	54-22
	45	10 VIII 49	44°56.5'N	16°11.5'W	2400	53-21
	48	11 VIII 49	46°44'N	12°54'W	2250	54-25
	50	12 VIII 49	47°49'N	10°18'W	2095	54-26
	54	19 VIII 49	51°11'N	14°33.1'W	350	54-28
	57	20 VIII 49	52°06.8'N	20°21'W	2040	54-30
	60	21 VIII 49	53°04.6'N	26°16.8'W	1900	54-32
	63	22 VIII 49	53°52'N	31°54'W	1440	53-20
	66	23 VIII 49	50°43.2'N	31°13'W	1850	54-34
	69	25 VIII 49	47°19.5'N	30°26.5'W	1330	—
	72	26 VIII 49	43°45.5'N	29°09'W	1600	54-37
	75	29 VIII 49	39°10'N	27°43'W	645	53-35
	78	2 IX 49	37°11.8'N	32°04.9'W	1200	54-40
	81	3 IX 49	36°51.8'N	36°51.2'W	1750	53-38
	84	5 IX 49	36°14.5'N	44°50.1'W	2500	54-43
	87	6 IX 49	34°43.6'N	51°26.6'W	2390	53-41
	90	7 IX 49	35°06.8'N	58°03.5'W	2480	54-46
5	1	15 II 50	34°41.8'N	70°00.6'W	—	58-2
	2	18 II 50	26°12.1'N	69°08.0'W	—	—
	3	22 II 50	16°33.0'N	66°33.1'W	2350	—
	4	23 II 50	12°16.0'N	62°50.0'W	1600	58-9
	5	28 II 50	11°28.0'N	59°19.8'W	1010	58-10
	6	1 III 50	16°19.3'N	54°28.2'W	2950	58-11
	7	3 III 50	21°16.2'N	57°54.1'W	2770	59-20
	8	5 III 50	26°20.1'N	57°08.1'W	3000	58-14
	9	6 III 50	31°18.0'N	56°28.2'W	2965	59-23
	10	8 III 50	36°15.5'N	55°56.5'W	2850	58-17
	11	10 III 50	41°16.5'N	55°08.5'W	2850	59-25
	12	16 III 50	41°53.1'N	50°03.9'W	2000	58-21
	13	17 III 50	38°53.5'N	44°28.0'W	2775	59-28

(Continued)

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Table 1 (Cont'd)

Cruise	Acoustic Station	Date (start)	Latitude	Longitude	Water Depth (fm)	Hydrographic Station No.
5	14	19 III 50	35°23.0'N	57°15.2'W	1500	59-30
	15	20 III 50	35°13.6'N	53°46.3'W	1390	59-31
	16	23 III 50	36°22.0'N	29°59.0'W	1700	59-32
	17	28 III 50	42°31.5'N	22°45.2'W	2000	59-34
	18	30 III 50	46°41.0'N	18°38.0'W	2400	59-36
	19	31 III 50	47°50.6'N	15°00.2'W	2490	59-37
	20	28 IV 50	19°32.2'N	22°51.0'W	2180	59-60
	21	30 IV 50	24°52.5'N	28°19.5'W	3000	59-35
	22	4 V 50	30°02.5'N	35°10.0'W	2210	59-63
	23	6 V 50	29°56.2'N	42°59.3'W	1660	59-65
	24	8 V 50	30°49.6'N	52°08.3'W	2850	59-67
	25	10 V 50	31°57.9'N	60°58.0'W	2620	59-60
7	2	23 XI 50	29°11.0'N	70°20.0'W	2860	-
	3	26 XI 50	19°32.0'N	67°55.0'W	2000	62-1
	5	28 XI 50	14°14.3'N	72°14.7'W	1800	63-6
	6	29 XI 50	13°51.1'N	75°23.5'W	2100	63-5
	7	1 XII 50	17°11.6'N	81°12.9'W	710	63-7
	8	3 XII 50	23°35.4'N	83°53.6'W	1200	63-9
8	1	4 II 51	31°43.9'N	67°32.1'W	2750	65-1
	2	6 II 51	30°24.5'N	61°08.0'W	2800	65-3
	3	8 II 51	30°38.5'N	53°15.5'W	3020	65-4
	4	9 II 51	30°23.0'N	49°09.0'W	2500	65-5
	7	15 II 51	30°25.0'N	30°44.0'W	2300	64-9
	8	18 II 51	31°55.0'N	22°59.0'W	2850	65-11
	9	20 II 51	32°49.0'N	18°55.0'W	1880	64-11
	10	21 II 51	33°57.0'N	15°19.0'W	2400	64-12
	11	22 II 51	35°27.0'N	7°33.0'W	750	64-13
	12	4 III 51	36°00.0'N	10°12.0'E	250	65-27
	13	8 III 51	35°23.0'N	22°39.0'E	2040	64-18
	14	9 III 51	36°52.0'N	18°20.0'E	1970	64-19
	15	11 III 51	39°03.0'N	14°31.0'E	1850	65-21
	16	12 III 51	41°38.0'N	10°25.0'E	800	64-21
	17	22 III 51	37°41.0'N	00°30.0'E	1300	65-26
	18	27 III 51	39°43.0'N	11°19.0'W	2240	64-26
	19	29 III 51	44°39.0'N	7°56.0'W	2620	64-27
	20	11 IV 51	46°54.4'N	9°32.0'W	500	65-31
	21	12 IV 51	46°25.0'N	12°10.0'W	2250	65-32
	22	13 IV 51	43°00.0'N	18°40.0'W	2350	64-33
9	23	19 IV 51	32°34.0'N	30°55.0'W	2250	64-36
	24	21 IV 51	32°37.0'N	36°47.0'W	1740	64-37
	25	25 IV 51	32°50.0'N	53°39.0'W	2550	65-41
	26	27 IV 51	32°46.0'N	59°06.0'W	2640	64-41
	1	2 VII 51	41°20.0'N	59°16.0'W	2600	66-2
	3	4 VII 51	44°42.0'N	47°23.0'W	2000	67-4
	4	6 VII 51	49°49.5'N	43°15.0'W	2250	67-6
	5	8 VII 51	54°20.0'N	38°15.0'W	1480	66-8
	6	9 VII 51	56°51.0'N	34°58.0'W	1000	67-8
	7	12 VII 51	58°19.0'N	33°13.0'W	950	67-9
	8	14 VII 51	62°20.0'N	27°37.0'W	800	67-10
	9	20 VII 51	59°39.0'N	22°46.0'W	1300	66-13
	10	22 VII 51	54°10.0'N	21°00.0'W	1500	66-15
	11	24 VII 51	45°22.3'N	19°24.2'W	2300	67-15
	12	26 VII 51	40°15.0'N	18°52.0'W	3000	67-16
	13	2 VII 51	38°55.4'N	16°24.1'W	2950	67-18
	14	3 VII 51	41°47.6'N	15°59.8'W	2875	66-21
	15	4 VIII 51	44°11.3'N	15°48.6'W	3000	67-19
	16	6 VIII 51	46°25.6'N	15°18.0'W	2400	66-22
	17	7 VIII 51	50°18.7'N	14°37.7'W	2300	66-23

(Continued)

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Table 1 (Cont'd)

Cruise	Acoustic Station	Date (start)	Latitude	Longitude	Water Depth (m)	Hydrographic Station No.
9	18	8 VIII 51	55°21.5'N	15°43.5'W	1900	64-24
	20	5 IX 51	43°21.8'N	29°53.7'W	1760	67-25
10	1	30 II 52	47°42.0'N	43° 1.0'W	2100	68-1
	2	2 II 52	54° 4.0'N	34°34.0'W	1150	68-2
	3	4 II 52	58°00.0'N	29° 5.0'W	1260	68-4
	4	5 II 52	60°43.0'N	25°00.0'W	1100	68-6
	5	8 II 52	56°24.0'N	18°42.0'W	1350	68-7
	6	10 II 52	54°58.0'N	12°30.0'W	1600	68-9
	7	11 II 52	57°00.0'N	12°27.0'W	1235	68-10
	8	21 II 52	61°21.0'N	10°36.0'W	650	68-14
	9	27 II 52	65° 1.0'N	2°36.0'W	1600	68-16
	10	28 II 52	65°45.0'N	0°17.5'W	1309	69-17
	11	7 III 52	60° 7.0'N	5°57.0'W	610	68-18
	13	16 III 52	44°57.0'N	13°37.0'W	1900	68-23
	15	24 III 52	39°15.0'N	14°40.0'W	2520	69-25
	16	25 III 52	40°21.0'N	23°18.0'W	2270	69-27
	17	30 III 52	41°24.0'N	40° 9.0'W	2600	68-30
	18	1 IV 52	41°59.0'N	47°44.0'W	2010	69-38
11	1	14 VI 52	42°35.0'N	58° 7.0'W	1450	--
	2	16 VI 52	49° 8.0'N	48°37.0'W	1300	70-1
	3	18 VI 52	56° 5.0'N	41°40.0'W	1920	71-2
	4	20 VI 52	59°59.0'N	34°11.0'W	1330	70-4
	5	22 VI 52	62° 9.0'N	22°20.0'W	870	70-6
	6	23 VI 52	62°16.0'N	15°25.0'W	1200	70-7
	7	24 VI 52	61°18.0'N	10°39.0'W	630	71-7
	8	8 VII 52	66°22.0'N	3°23.0'E	840	71-11
	9	11 VII 52	70° 3.0'N	15°45.0'E	1300	70-34
	10	14 VII 52	73°39.0'N	8°59.0'E	1350	70-38
	11	16 VII 52	70°28.0'N	8° 2.0'E	1610	70-39
	12	18 VII 52	75°32.0'N	0°53.0'E	960	71-42
	13	20 VII 52	73°47.0'N	10° 9.0'W	1700	70-44
	14	21 VII 52	72°19.0'N	3°31.0'W	1330	71-45
	15	23 VII 52	68°55.0'N	4° 1.0'E	1810	71-46
	16	29 VII 52	66°12.0'N	3°33.0'E	820	71-47
	17	1 VIII 52	68°14.0'N	1°13.0'W	1960	71-73
	18	20 VIII 52	55°36.0'N	11°43.0'W	1550	71-82
	21	26 VIII 52	50°55.0'N	41°41.0'W	2350	71-88
12	2	15 II 53	42°38.0'N	60°35.0'W	1840	72-2
	4	18 II 53	35°53.4'N	62°44.2'W	2750	73-6
	5	19 II 53	34°14.2'N	63° 6.7'W	2750	72-3
	6	3 III 53	27° 7.5'N	57°10.0'W	3310	73-9
	7	3 III 53	26°00.0'N	58°54.1'W	3350	72-6
	8	5 III 53	22°40.8'N	57°12.9'W	3350	73-10
	9	7 III 53	19°23.0'N	58°57.0'W	2620	72-8
	10	9 III 53	17° 6.2'N	58°49.4'W	2975	73-14
	11	10 III 53	14°47.1'N	59°30.0'W	1680	72-12
	12	18 III 53	12°24.0'N	60°32.3'W	1350	72-14
	13	19 III 53	14°31.8'N	60°18.5'W	1370	73-19
	14	20 III 53	16°41.0'N	60°42.0'W	3000	72-17
	15	22 III 53	18°20.0'N	62° 9.0'W	2840	72-18
	16	3 IV 53	25°55.5'N	67°30.0'W	2940	73-26
	17	4 IV 53	24°32.1'N	69°19.0'W	3050	72-21
	18	5 IV 53	26°25.1'N	69°51.1'W	2975	73-27
	19	6 IV 53	25°14.0'N	71°38.7'W	3000	72-22
	20	7 IV 53	27° 6.1'N	72°15.9'W	2760	73-28
	21	15 IV 53	29°41.1'N	75°14.1'W	2565	73-30
	22	16 IV 53	31°41.1'N	76° 7.5'W	1500	73-31

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b. Low Frequency

Date <sup>c</sup>	Latitude	Longitude	Broad-Band Source <sup>d</sup>		Range (km)	Hydrophone Depth (ft)
			Type	Range (km)		
18 VII 52	75°00'N	1°00'E	Shren	0.5-70	70	50; 500
1 VIII 52	64°00'N	1°00'W	Shren	0.5-70	70	50; 500
14 II 53	42°25'N	60°32'W	Mk 4v	0.5-33	42	—; 500
19 II 53	33° 7'N	62°34'W	Shren	0.5-60	60	—; 500
20 II 53	33°39'N	63°23'W	Mk 4v	0.5-80	80	—; 500
21 II 53	30°12'N	64°37'W	Mk 4v	70-9	9	50; 500
				9-49	49	50; 500
23 II 53	32°22'N	65° 2'W	None	—	80	—; 500
4 III 53	23°35'N	50°34'W	None	—	87	50; 500
8 III 53	18°13'N	56°34'W	None	—	63	50; 500
10 III 53	15°17'N	59°34'W	None	—	86	—; 500
18 III 53	12°47'N	60°33'W	Shren	0.5-16	70	—; 500
21 III 53	16°49'N	60°43'W	None	—	80	50; 500
29 III 53	18°31'N	65° 3'W	Mk 4v	4.0-90	90	50; 500
30 III 53	18°31'N	66° 3'W	Mk 4v	4.0-70	70	—; 500
31 III 53	18°31'N	66° 3'W	Mk 4v	2.0-33	33	50; 500
3 IV 53	25°51'N	67°28'W	Mk 4v	0.5-34	34	50; 500
4 IV 53	24°32'N	69°24'W	None	—	80	50; 500
5 IV 53	26°24'N	69°32'W	Mk 4v	0.5-80	80	50; —
6 IV 53	25°14'N	71°39'W	Mk 4v	0.5-76	76	50; —
9 IV 53	23°38'N	73°26'W	Mk 4v	0.5-63	63	50; —
13 IV 53	23°27'N	76°15'W	Mk 4v	>50-80	80	50; —
16 IV 53	29°36'N	75°24'W	Mk 4v	0.5-80	80	—; 500
20 IV 53	30° 4'N	73°54'W	Mk 4v	0.5-74	74	50; —
21 IV 53	36°24'N	72°50'W	Mk 4v	0.5-88	88	50; —
21 IV 53	37°36'N	72°53'W	Mk 4v	0.5-90	90	50; —
22 IV 53	38°23'N	72°58'W	Mk 4v	0.5-75	75	50; —

<sup>c</sup> Stations conducted on 18 VII 52 and 1 VIII 52 were occupied on Cruise ELEVEN. All other stations occupied on Cruise TWELVE.

<sup>d</sup> All Shren and Mk 4v noise number runs have been processed.

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In addition, all the wartime acoustic and environmental records of the University of California Division of War Research have been transcribed on IBM cards. The shallow-water propagation surveys made in Fishers Island Sound by the Columbia University Division of War Research and the East Coast and Gulf of Mexico shallow-water propagation surveys carried out by WHOI have been transcribed to punched-card form. An inventory of these propagation and environmental data in the Laboratory's IBM punched-card file is presented below.

UCDWR Acoustic Data (Card Layout Forms, Figs. 9-12, USL Report No. 147)		
		No. of Cards
Low Frequency: 0.2, 0.6, 1.0, 7.5, and 22.5 kc	Acoustic	1861
	Environmental	436
High Frequency: 10, 14, 20, 40, 56, and 60 kc but primarily 36 kc	Acoustic	4112
	Environmental	1501
		7950

Fishers Island Sound and Block Island Sound Shallow-Water Data  
(Columbia University Division of War Research)

	Number
Environmental Cards	30
Acoustic Data Cards	104

Woods Hole Oceanographic Institution  
Shallow-Water Acoustic Data

	Number
Bathythermograph Cards	863
Environmental Cards	300
Acoustic Cards	500

During the year 1951, a set of QHBA performance charts was prepared. Included in this set were monthly tables and charts of expected sweep width for QHBA-equipped surface vessels for four operational submarine-depth intervals. Such strategic charts may be used in comparing convoy routes from the point of view of sonar protection and also for submarine operations.<sup>3</sup> This information was transmitted to the Hydrographic Office for publication and dissemination.<sup>4</sup>

<sup>3</sup> Sample charts may be found in USL Report No. 147 (CONFIDENTIAL).

<sup>4</sup> See USL letter to the Hydrographic Office, "Status of Project AMOS," ser. 1110-036, 1 November 1951 (CONFIDENTIAL).

In preparing these charts it was necessary to establish a QHBA figure-of-merit measurements program, which extended well into the year 1952.<sup>5</sup> As a result, the figures of merit of 27 destroyer-type ships of the Fleet were obtained under various environmental and ship operating conditions. Approximately 200 sonar-men participated in these operations. In addition to the data required for the strategic operational charts, many other important results were obtained from this figure-of-merit program. Significant (uncovered) factors were uncovered, the importance of a clear water dome was emphasized, and the importance of a more rapid audio-beam search than that prescribed by QHBA doctrine was established.

An analysis was also made of the propagation data with respect to variable-depth sonar applications.<sup>6</sup> Project AMOS data were applied to the problem of determining the optimum depth for variable depth sonar and the gains to be expected for a system operating at this depth.

Another study carried out in the year 1952 concerned the expected operational performance of echo-ranging sonars at 5 kc and 10 kc.<sup>7</sup> In this work, aimed at efficient system design, Project AMOS propagation-loss data at acoustic frequencies of 2.2, 8, 16, 21, 25, and 29 kc were analyzed as a function of range and operational submarine-depth intervals for various ET AMOS code classes. A study was also made of the expected propagation-loss anomaly, at various ranges, arising from bottom-reflection acoustic paths in deep water. These propagation data were applied to monthly environmental statistics for the North Atlantic Ocean area between 30° N and 40° N in order to obtain the expected median range for four equipment figures of merit (140, 150, 160, and 170 db) for 5-kc and 10-kc, hull-mounted, echo-ranging sonar systems. In the present report, a modified version of this study has been prepared for systems at 8 and 14 kc.<sup>8</sup>

<sup>5</sup> This program is described by M. Schultis, F. S. White, Jr., and R. A. Spang in QHBA Figure-of-Merit Tests, USL Report No. 187, 3 April 1953 (CONFIDENTIAL).

<sup>6</sup> See Appendix A of Report on the Status of Project AMOS (1 January - 31 December 1952), by R. W. Marsh, Jr., and M. Schultis, USL Report No. 168, 3 April 1953 (CONFIDENTIAL).

<sup>7</sup> See USL Report No. 169 (CONFIDENTIAL), Appendix B.

<sup>8</sup> See Study F.

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Bottom-reflection paths at these frequencies have been found to be less important than reported earlier.

Also in connection with this program a study concerned with the temperature dependence of attenuation was prepared.<sup>9</sup> The study of Project AMOS propagation measurements made in isothermal water shows that the temperature of the water has an important effect upon the propagation loss, the loss being greater in colder water.

In addition, propagation loss in isothermal layers depends slightly, but consistently, upon projector and receiver depths. Data which showed the distribution of propagation loss at frequencies from 2 to 25 kc, at ranges from 1 to 33 kyd, at projector and receiver depths from 20 to 500 ft, and at water temperatures from 35° F. to 70° F. were presented. The probable error under prescribed conditions was 3 db. The temperature effect is in good agreement with a model exhibiting a single relaxation process.<sup>10</sup> Also, a wave theoretical treatment of the propagation problem shows that certain features of the observed depth dependence are explicable.

Analyses of low-frequency noisemaker runs made on certain of the AMOS cruises were also carried out.<sup>11</sup> The purpose of these runs was to determine attenuation values for propagation of low-frequency (100 to 10,000 cps) sound under various oceanographic conditions. Topics of interest include propagation in surface channels, channeling of sound between the ocean surface and bottom, distances between focus points at various latitudes, and modification or design of equipment for better production and reception of low-frequency sound in the ocean.

The broad-band magnetic-tape records of low-frequency noisemakers are being processed with automatic equipment. The end product is a set of IBM punched cards, at approximately 250-yard intervals, which contain the measured level in ten frequency bands from approximately 200 cps to 10,000 cps; the actual frequencies depend on the source used. These runs can extend out to about 80 kyd, and background noise levels are entered

periodically in place of the noisemaker levels. Level-versus-range plots have been made for the card data by means of the automatic plotting machine. Range values were obtained from range-versus-travel time curves drawn from the bomb-drop data. Sound-velocity-versus-depth plots were completed for all deep Nansen cast data of Cruise TWELVE, and some ray computations were made therefrom.<sup>12</sup>

From the level-versus-range plots, levels have been read and tabulated for 0.25-kyd increments from 1 to 2 kyd, 0.5-kyd increments from 2.0 to 5.0 kyd, 1-kyd increments from 5 to 10 kyd, 2.5-kyd increments from 10 to 20 kyd, and 5-kyd increments from 20 kyd to the conclusion of the run. In the focus region, readings are tabulated at 0.25-kyd range increments.

Source levels for the two sources have been determined by assuming spherical spreading to 1000 yd for each station and extrapolating the value at 1000 yd back to 1 yd. An average value for each frequency band was then computed from the extrapolated values.

Plots of measured level plus computed spreading and absorption loss have been made against the grazing angle at the ocean bottom for frequencies of 1, 2, and 8 kc for those stations for which a reasonable estimate of the ranges at which bottom reflection paths predominate could be made.

An analysis of AMOS transmission data in the 2- to 25-kc frequency region, including propagation by way of the bottom, has been completed.<sup>13</sup> It is believed that, for the most part, propagation at these frequencies in deep water is fairly well understood in terms of environmental factors. In another report,<sup>14</sup> contours of transmission loss have been plotted for ten frequencies and three projector depths, for a standard temperature (50° F.) and a standard layer depth (100 ft). Correction charts have been plotted for each frequency for the correction required because of changes in layer depth, temperature, and sea state. Values for the absorption coefficient as a function of frequency and temperature are also included. These data have been used and will continue to be used in the future, in the frequency range covered, for

<sup>9</sup> See USL Report No. 188 (CONFIDENTIAL), Appendix C.

<sup>10</sup> A formula for the temperature effect on absorption including relaxation and viscous terms is presented in Study A of this report.

<sup>11</sup> See Studies I and J of this report.

<sup>12</sup> For the ray methods used, see Studies H and J of this report.

<sup>13</sup> See Study A.

<sup>14</sup> See Study B.

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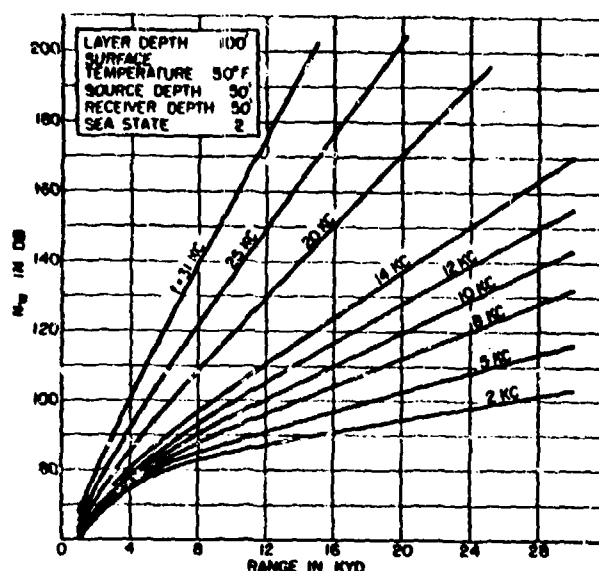


Fig. 2 - Transmission Loss vs. Range for Standard Conditions

operational applications involving echo-ranging, variable-depth sonar, and passive submarine sonar. It is important to have a standard reference of transmission loss related to range and frequency. Figures 2 and 3, applying to specific environmental conditions which are typical of those occurring naturally, are recommended for this purpose.

The AMOS propagation results were used to construct lateral range curves for hull-mounted, echo-ranging sonars at various frequencies and figures of merit for submarines at periscope depth and at the best depth for avoiding detection.<sup>15</sup> The curves apply to specific layer depths and surface temperatures. Such curves were used by CAPT S. D. B. Merrill to space the ships of his screen in AsDevEx-I. A subsequent study of AsDevEx-I and other available data showed that predicted and

<sup>15</sup> See Study E.

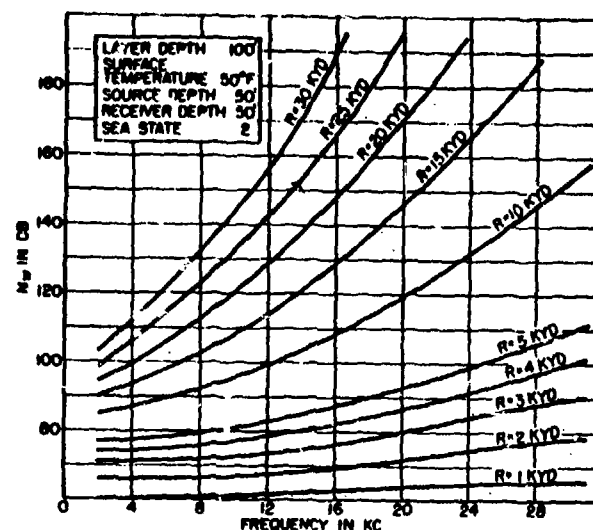


Fig. 3 - Transmission Loss vs. Frequency for Standard Conditions

measured range performance compared favorably at all frequencies over a range of propagation conditions.<sup>16</sup>

As a result of its experience, the Laboratory has been assigned the problem of preparing a sonar range prediction manual to replace the existing manual, *Sonar Prediction with the Bathythermograph* (NAVSHIPS 900,111, 1 October 1947, CONFIDENTIAL). The Laboratory also plans to use its propagation information in the analysis of operational submarine array sonar contact reports. All such reports received to date have been key-punched, checked, and listed. Listings have been distributed to ComSubPac, ComSubLant, SubDev-GruTWO, and Bureau of Ships.

<sup>16</sup> See Study F. This study was delivered as a paper at the Ninth Navy Symposium on Underwater Acoustics, 17 June 1954, at the Naval Research Laboratory, Washington, D. C.

## PROPAGATION ANALYSIS AND SONAR RANGE PREDICTIONS

The nine studies appended to this report represent work done on Project AMOS during the years 1953-54 in the fields of propagation analysis and sonar range predictions. Project AMOS collected

large quantities of propagation-loss data on extensive cruises to all parts of the North Atlantic in all seasons in order to extend our knowledge of propagation, both with respect to acoustic fre-

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quency and depth of endpoint positions of the propagation path. As each cruise was completed, the data were examined and analyzed in the light of previous cruise results, existing knowledge, and contemporary research by other working groups.<sup>17</sup>

The final analysis, as given in Study A, was considered to be consistent with information then available. The propagation-loss data obtained from AMOS cruises at discrete frequencies of 2.2, 8, 16, and 25 kc were analyzed and interpreted according to a definite model. Equations of propagation loss were obtained for the model and fitted with semi-empirical coefficients.

The steps used to arrive at this model consisted of (1) finding the important acoustic-oceanographic variables, (2) studying acoustic patterns in situations when one of these variables dominated, and (3) making the simplest assumptions regarding the acoustic interrelation of these variables and adding complications only when the exigency of incorporating a large body of data into the model so required.

The model was constructed from several modes of propagation, each of which became important under certain conditions of the wide range of geog-

raphy and season covered by the AMOS cruises. While other observed effects could be included readily, it was found that these occurred in an extreme way only in certain localities. It was felt that to introduce other parameters in order to take these into account would unduly complicate the analysis and would not improve the prediction capabilities for most of the localities and seasons. In particular, the magnitude of the thermocline gradient was an important variable of this type. The propagation data for all thermocline gradients were grouped in one class. In addition, the propagation data for all temperature gradients more positive than  $-0.3^{\circ}$  F./100 ft were considered in the mixed-layer class. It is recognized that these assumptions must be modified for work in particular localities.

The important oceanographic-acoustic variables for the frequencies under study were found to be isothermal layer depth, temperature, and sea state. The temperature effect was best studied in the situation where a constant temperature prevailed to very great depths. Under such conditions, it was found that the acoustic field was generally constant with depth at a fixed range out to ranges of the order of 24 kyd, the limiting range of the experimental measurements. In such circumstances, the attenuation constants were computed and plotted against temperature for the four frequencies. These data were then considered with respect to existing data of the same kind and to other laboratory measurements. The parameters of a theoretical expression involving the sum of a viscous contribution and a relaxation phenomenon contribution were then determined. Formula (7) of Study A represents the resulting expression. Figures 10 and 11 of Study B and Fig. 3 of Study A are graphs based on this formula. It should be noted that the final value of the relaxation coefficient is less than the value 0.76 presented in an earlier work.<sup>18</sup>

The next variable studied was isothermal layer depth. In shallower layers than those considered in the previous paragraph, there is a residual attenuation loss which depends on layer depth, range, frequency, receiver and projector depth, and sea state. It was quite obvious from the data that, at a fixed range and projector and receiver depth, the residual attenuation increased the higher the sea state, the higher the frequency, and the shallower the layer depth.

<sup>18</sup> See Appendix C, USL Report No. 188.

<sup>17</sup> Some of the reports and articles consulted during the propagation analysis were: "Transmission," Part I, *Physics of Sound in the Sea*, Summary Technical Report of Division 6, NDRC, vol. 6, 1946 (UNCLASSIFIED); *Principles and Applications of Underwater Sound*, Summary Technical Report of Division 6, NDRC, vol. 7, 1946 (RESTRICTED); Sonar Data Division, UCDWR, "The Influence of Thermal Conditions on the Transmission of 24-kc Sound," UCDWR U307, 16 March 1945 (CONFIDENTIAL); R. J. Urick, "Sound Transmission Measurements at 8 and 16 kc in Caribbean Waters, Spring 1949," NRL Report 3556, 11 November 1949 (CONFIDENTIAL); R. J. Urick, "Sound Transmission Measurements in the Long-Island-Bermuda Region," NRL Report 3630, 6 September 1950 (CONFIDENTIAL); R. J. Urick, "Sound Transmission to Long Ranges in the Ocean," NRL Report 3729, 6 September 1950 (CONFIDENTIAL); H. R. Baker, A. G. Pieper, and C. W. Searfoss, "Measurements of Sound Transmission Loss at Low Frequencies 1.5 to 5 kc," NRL Report 4225, 23 September 1953 (CONFIDENTIAL); W. C. Meecham, W. H. Kelly, J. R. Frederick, "An Investigation of the Sound Transmission Loss in and below an Isothermal Layer," Technical Report Project M936, 7 July 1953, Engineering Research Institute University of Michigan (CONFIDENTIAL); and J. R. Frederick, J. C. Johnson, W. H. Kelly, "An Analysis of Underwater Sound Transmission Data," Interim Technical Report, Project M936, April 1954 (No. 1936-I-T), Engineering Research Institute, University of Michigan (CONFIDENTIAL).

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Thus, some kind of scattering phenomenon which depended directly on sea state, and inversely on volume, since a greater loss was observed for shallower layers, seemed to be operative. This could be explained most easily on the basis of a surface scattering phenomenon. A possible mechanism for volume scattering could be visualized whereby sea state somehow introduced volume scattering elements so that shallower layers had more intense scattering centers. Assuming that the mechanism is one of surface scattering, the loss can be related to the degree of contact that the acoustic energy has with the sea surface as well as to the size and frequency of the surface irregularities. For an omnidirectional source, the fraction of rays which are refracted upwards to meet the surface depends on the layer depth. The range of the limiting ray is a measure of this fraction. This range between successive surface contacts of the limiting ray turns out to be the  $\sqrt{L}/2$  in kiloyards if  $L$  is expressed in feet. Thus,  $\sqrt{L}$  is a suitable scaling factor for range if the degree of contact of energy with the surface is a satisfactory measure of the energy loss from a surface channel. By further scaling the projector and receiver depths to layer depth, it would seem possible to normalize the data for all layer depths at any single frequency. This was done in the analysis leading to Study A and proved to be a reliable way of translating a large amount of data into a single propagation class.

Three propagation zones were recognized in connection with propagation in the presence of isothermal layers. The near zone is defined by a limiting ray leaving a source and returning to the surface after touching the bottom of the surface channel. In this zone energy travels between points by a direct path and spreads spherically. In the far zone, energy is propagated down the channel after two or more contacts with the surface, and the decay of the acoustic field can be represented by a scattering loss coefficient added to the temperature absorption term at a fixed frequency. Cylindrical spreading holds in this region. The intermediate zone is a zone of transition between the near zone with spherical spreading and the far zone with cylindrical spreading and surface scattering loss. A semiempirical depth-loss factor was obtained for each zone, depending on the ratio of the scaled range in any zone to the scaled zone

width. The formulas provide a propagation loss for any projector-receiver depth pair.

When both ends of the propagation path are not in the isothermal layer, energy may penetrate below the layer by way of surface scattering, diffractive leakage from the surface channel, or diffractive leakage from the direct beam. The first two cases are taken care of by the depth-loss factor for each of the propagation zones of the previous mode.

The case of diffractive leakage from the direct beam must be treated individually when the mode of propagation involving downward refraction prevails. Downward refraction occurs in the presence of a negative velocity gradient directly below the surface when no layer is present or in the thermocline below an isothermal layer. Thus, when one end of the path is in the surface channel and one end is beneath the surface channel, this mode applies to the portion of the energy which is split at the limiting ray and is refracted downwards. The formulas for propagation loss for this mode have been based on a theoretical expression derived previously.<sup>19</sup> The term in the brackets of Formula (2) of Study A has been fitted with empirical coefficients for an average velocity gradient. The equation for the limiting ray under these conditions is:

$$R = 1/5 \sqrt{|Z_s - L|} + 1/5 \sqrt{|Z_r - L|}$$

Since the acoustic intensity may be dominated either by leakage from the surface channel or diffracted energy from the downward refracted beam, computations must be made for both of these modes when both ends of the propagation path are not in the layer. The mode producing the lesser propagation loss is the one that prevails.

An important mode of propagation for variable-depth sonar applications occurs when a depressed or internal sound channel is present and both ends of the propagation path are in the channel. The axis of the channel is the depth of a sound velocity minimum. This condition usually occurs when the temperature gradient levels off below a steep thermocline and the pressure effect on sound velocity with increasing depth takes over. The SOFAR channel is such a case in point. It has

<sup>19</sup> See H. W. Marsh, Jr., *Theory of the Anomalous Propagation of Acoustic Waves in the Ocean*, USL Report No. 111, 12 May 1950 (UNCLASSIFIED), p. 35.

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been found from the AMOS data that for shallow, depressed channels the width of these channels is approximately equal to the depth of the channel axis. This model has been used to obtain an expression for the propagation loss, which is the same as that for the near zone of the surface channel. It should be noted that this expression holds on the average.

Finally, there are situations where energy is propagated between two points by way of the bottom. Data from several sources were combined to yield a set of curves of bottom loss versus bottom-grazing angle for frequencies from 125 cps to 32 kc. In using these curves, one calculates the spreading and absorption loss over the ray path for specular reflection on the bottom and inserts the appropriate bottom loss. For echo-ranging purposes, the one-way propagation loss computation must be doubled. Study D of this report presents a discussion of the data used in arriving at the bottom-loss curves.

An error analysis of the semiempirical formulas for computing propagation loss is given in Study C. It is shown there, on the basis of a sampling procedure, that the prediction method is reliable over the range of frequencies and ranges considered. Some reduction in probable error could be achieved perhaps for the downward refraction mode of propagation by taking the magnitude of the velocity

gradient into account, but this is hardly worth the additional complications.

Study F compares the performance of various echo-ranging sonars from the point of view of equipment figure of merit and range performance. In this paper, it is shown that the prediction method gives results which compare favorably with operational range performance data. Studies E, F, and G present three operational applications of Project AMOS results to surface vessel, echo-ranging sonar performance prediction problems.<sup>29</sup> In these studies the expected performance of echo-ranging sonars under various environmental and operational conditions is discussed.

Study H contains a very useful and interesting approach to the problem of ray tracing and field intensity computations. In Studies I and J these methods are applied especially to the energy propagated through the deep ocean by way of the SOFAR channel to focusing regions. A more detailed application of this theory is made to the data obtained in connection with the Project AMOS low-frequency broad-band noisemaker runs. It is shown that the quantitative features of the data can be explained by the theory.

<sup>29</sup> The concepts of "probability of detection" and "lateral range curves" are discussed in detail in USL Report No. 147.

## SUMMARY REPORT OF AMOS CRUISE TWELVE<sup>31</sup>

The Oceanographic Survey Unit for Cruise TWELVE consisted of the USS SAN TABLO (AGS-

<sup>31</sup> The summary report of AMOS Cruise TWELVE was prepared by LT E. C. Iselin, Jr., Hydrographic Survey Officer at the Underwater Sound Laboratory. The operation order for this cruise appears in letter from the Hydrographer to ComSUBLANT, "Technical Instructions for AMOS Cruise TWELVE; forwarding of," sec. 09483, 31 December 1952 (CONFIDENTIAL). The measurements to be taken on this cruise were proposed in USL letter to the Hydrographer, "AMOS Cruise 12; schedule of," sec. 1170-056, 14 November 1952 (CONFIDENTIAL).

30). CAPT W. D. Day (Commander Oceanographic Survey Unit); and the USS REHOBOTH (AGS-50), CAPT R. R. Snyder.

AMOS Cruise TWELVE was planned primarily from the standpoint of obtaining the maximum amount of acoustic data supported by the necessary oceanographic and seismic operations. The following measurements were proposed by the Laboratory:

- a. 27 Acoustic Event 1
- b. 27 Acoustic Event 8A

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- c. 27 Acoustic Event 3
- d. 27 Acoustic Event 6
- e. 5 Special Acoustic Events
- f. 2 Acoustic Event 8C

The total cruise time was 88 days. Of this time 64 were spent at sea.

The following Laboratory personnel participated in AMOS Cruise TWELVE:

The following itinerary was set for this cruise:

Date (1953)	Arrival-Departure	Place	USS SAN PABLO	USS REHOBOTH
			LT E. C. Iselin, Jr. ENS B. B. Halleck Mr. H. F. Bernier	ENS B. B. Nichols Mr. W. H. Thorp Mr. L. C. Maples Mr. F. G. Weigle Mr. O. P. Dickson Mr. S. F. Niedzwiecki
26 January	Departure	Norfolk, Va.		
30 January	Arrival	New London, Conn.		
7 February	Departure	New London, Conn.		
23 February	Arrival	Bermuda		
27 February	Departure	Bermuda		
13 March	Arrival	Trinidad, B.W.I.		
17 March	Departure	Trinidad, B.W.I.		
30 March	Arrival	San Juan, P. R.		
30 March	Departure	San Juan, P. R.		
10 April	Arrival	Nassau		
15 April	Departure	Nassau		
23 April	Arrival	Philadelphia, Pa.		

ENS Nichols transferred from REHOBOTH to SAN PABLO in Trinidad. Mr. H. Johnson, of WHOI, was embarked in REHOBOTH during the Norfolk-to-New London and Bermuda-to-Trinidad legs.

#### EVENT 1: FOUR-FREQUENCY TRANSMISSION-LOSS MEASUREMENTS

Twenty-two Event 1 stations were made on AMOS Cruise TWELVE. Since the multi-element line hydrophone was not available, an alternate operating procedure was developed. Briefly stated, pulses were transmitted while the transducers were raised from 500 feet to 20 feet. Receiving trans-

ducers were stationed at 20, 50, 100, 250, and 500 feet with one transmitting row for each receiving depth. Standard ranges for Event 1 were 3000, 8000, 12,000, 18,000, and 24,000 yards. When bathythermograph conditions were such that no transmissions were to be expected at 24,000 yards, an additional range of 5000 yards was taken.

#### EVENTS 4 AND 5: VERTICAL REVERBERATION MEASUREMENTS (12 KC) AND DEEP SCATTERING LAYER MEASUREMENTS

No Event 4 and Event 5 data were obtained. As a result of heavy pounding of the SAN PABLO during the first and second leg, the AN/UQN-1

fathometer transducer was damaged. A replacement was installed in Bermuda, but high-quality reception was not obtainable.

#### EVENT 6: VERTICAL TRANSMISSION AND SCATTERING LAYER MEASUREMENTS (8, 16, AND 30 KC)

No Event 6 data were obtained because of fathometer transducer difficulties on the REHOBOTH. At first these difficulties were attributed to crystal

failure, but later they were found to be caused by broken crystal leads.

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## EVENTS 8A AND 8B: LOW-FREQUENCY PROPAGATION MEASUREMENTS

A total of 25 Event 8 type measurements were made. Subdivided by types they were:

<u>Event 8A</u>	<u>Event 8B</u>
11 with Mk 4	4 with bombs only
3 partial runs with Mk 4	
7 runs with bombs only	

No complete siren runs were made. Repeated mechanical casualty to the siren and pump overheating problems precluded its effective use on AMOS Cruise TWELVE. One short run using the Mk 6 was made to obtain the "signature" of the device as a sound source.

The schedule included the six special events described below. Detailed reports of these events, complete with track charts and logs, are being prepared for distribution.

**ABLE (Site 1):** A combination of unsuitable weather and lack of coordination between the aircraft and Office of Naval Research resulted in failure to this event.

**BAKER:** Special Event BAKER started at 201244Z February, 120 miles northwest of Bermuda. During the course of the circular run and the final radial run into Bermuda, 360 bombs were fired. Except for time out of commission, the Mk 4 was operated intermittently according to schedule. The final bomb of Phase I was fired at 230538Z February. The depth of detonation of the SOFAR shots is doubtful. The detonators used were observed to give erratic results and caused detonation to vary from premature to none at all. Phase II started at 282015Z February. A total of 147 bombs were fired. The event ended at 020630Z March.

**CHARLIE:** This event was executed by the seismic personnel and will be reported by them. However, cursory analysis of the data shows no evidence supporting the existence of Echo Bank.

**DOG:** This event started at 222204Z March. One hundred and two bombs were fired. The Mk 4 operated one hour on, one hour off. No Mk 4 casualties were experienced. Phase I ended at 240100Z March. Phase II started at 301707Z March. The two runs (070° and 304°) were run in accordance with the planned schedule. Sixty bombs were dropped on each run. On the 400-mile run on bearing 007°, 260 bombs were fired. The event ended at 010043Z April.

**EASY:** Special Event EASY started at 081304Z April. Forty-three bombs were fired. The Mk 4 was operated according to schedule. Phase I ended at 091219Z April and Phase II started at 132212Z April. Seventy-eight bombs were fired. The Mk 4 operated without failure. The event ended at 142345Z. Upon completion of this event the signature run of the Mk 6 was made.

**ABLE: (Site 2):** To utilize time more economically it was decided to abandon the site of the first Event 8C. It was planned to conduct Special Event ABLE and Event 8C at Site 2. Event ABLE was almost completed when heavy weather caused abandonment of the site.

The following major material casualties and deficiencies were noted:

a. In order to keep the Mk 4 operative, continuing maintenance was required. Four diaphragms were used.

b. The Mk 6 can not be towed at speeds over 5 knots. It was not used except for the one signature run.

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# STUDY A

## SOUND TRANSMISSION AT FREQUENCIES BETWEEN 2 AND 25 KILOCYCLES PER SECOND<sup>1</sup>

by

H. W. Marsh and M. Schulkin

### INTRODUCTION

An analysis of AMOS transmission data in the 2- to 25-kc frequency region has been completed. The results of this analysis are presented in this

<sup>1</sup> This report, which was issued as USL Technical Memorandum No. 1110-110-54, 27 August 1954 (UNCLASSIFIED), is a revision of USL Technical Memorandum No. 1110-8-54, 14 January 1954 (UNCLASSIFIED).

memorandum. A comprehensive discussion of these results, including comparison with other existing data, and recommendations for applications will be given in a forthcoming Laboratory report.

### METHOD OF ANALYSIS

A definite model of the ocean as a transmitting medium has been used in carrying out this analysis. Reference to Fig. 1 will show that there are

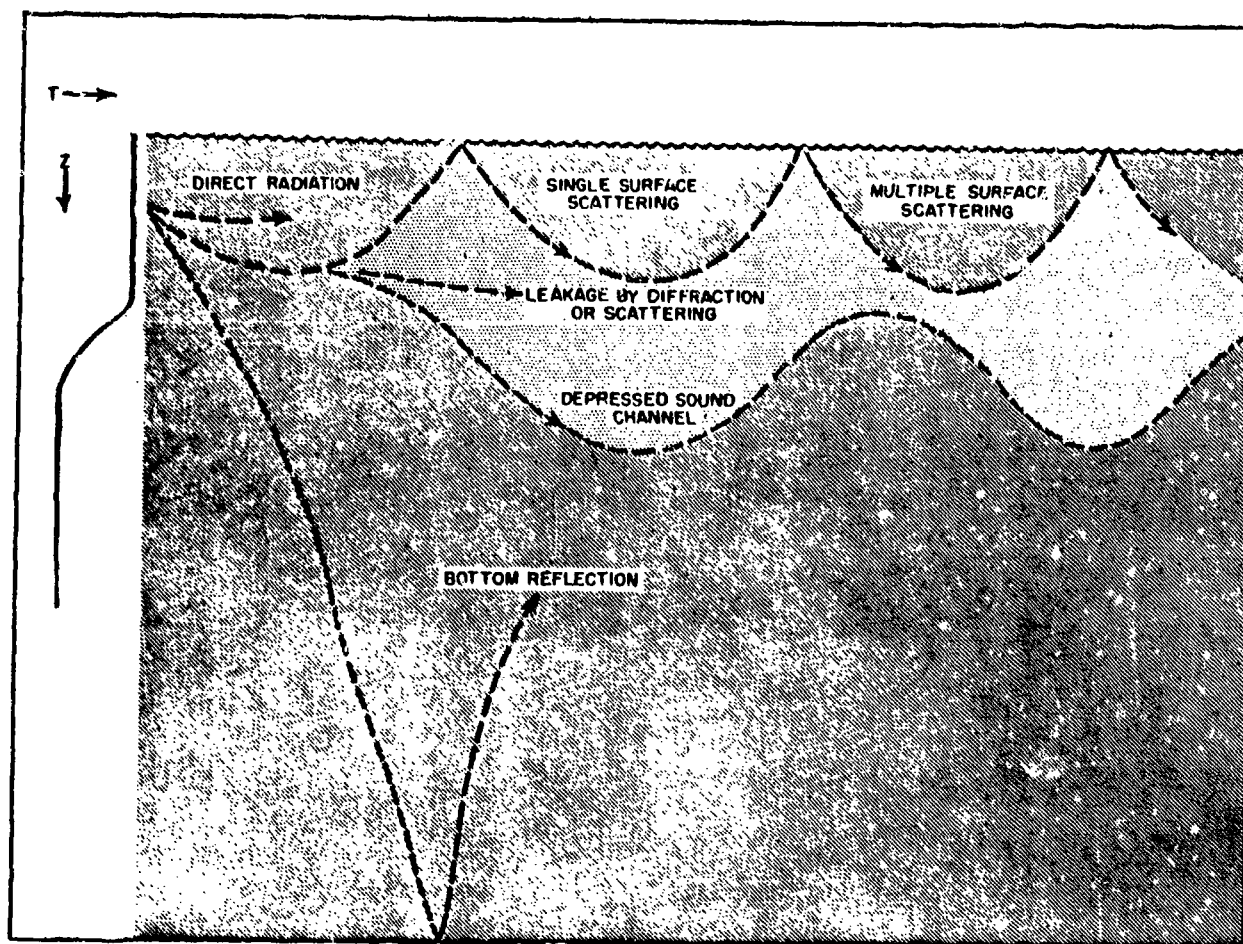


Fig. 1 - Modes of Sound Transmission

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several modes of propagation which determine transmission conditions under any given set of circumstances. Sometimes the different modes are of comparable importance and must be combined in order to estimate the net sound field. At other times the sound field is dominated by a single mode of transmission.

In the present analysis an effort has been made to study the various modes separately. This can be done to a great degree by a proper selection of data according to the different oceanographic factors and according to the geometry and acoustic frequency associated with the data. Those factors which have been determined to be of importance are:

- Depth of isothermal (surface) layer
- Sea state (wind force)
- Depth of axis of depressed sound channel
- Depth of ocean bottom
- Water temperature
- Range
- Depth of source
- Depth of receiver
- Acoustic frequency

By scaling and by certain laws of combination, it is possible to reduce substantially the number of parameters required to characterize any particular mode. Thus, it is possible to prepare a limited set of charts or tables which, together with a small amount of computation, can be used to determine transmission loss under any prescribed condition lying within the framework of the analysis.

### THE BASIC MODES OF TRANSMISSION

Transmission via modes associated with the surface isothermal layer and various orders of surface scattering (including negative surface gradient) may be scaled to layer depth and described in terms of a few simple formulas, which are listed after the definitions below. Source and receiver depths may be used interchangeably in applying these formulas. However, the conditions applying to the formulas are stated only for  $Z_0 \leq Z$ .

The following definitions and symbols will be used:

#### Basic Variables

Surface Isothermal Layer Depth (ft)	$L$
Sea State	$S$

Depth of Axis of Depressed Sound Channel (ft)	$D$
Depth of Ocean Bottom (fm)	$B$
Water Temperature (deg. F.)	$T$
Range (kyd)	$R$
Depth of Source (ft)	$Z_0$
Depth of Receiver (ft)	$Z$
Acoustic Frequency (kc)	$f$
Relaxation Frequency (kc)	$f_T$
Transmission Loss (db)	$N_w$
Spreading Loss (db)	$\begin{cases} 10 \log R, \\ 20 \log R \text{ (Fig. 2)} \end{cases}$
Absorption Coefficient (db/kyd)	$a$ (Fig. 3)
Scattering Coefficient (db/kyd)	$a_s$ (Fig. 4)
First Depth-Loss Factor	$G$ (Fig. 5)
Second Depth-Loss Factor	$H$ (Fig. 6)
Bottom Loss (db)	$N_B$ (Fig. 7)

#### Scaled Variables

$$r = R/\sqrt{L},$$

$$x_0 = \sqrt{Z_0}/\sqrt{L},$$

$$z = \sqrt{Z}/\sqrt{L},$$

$$r_1 = \frac{1}{4} [2 - z - x_0]; \quad z \leq 1, x_0 \leq 1;$$

$$r_1 = \frac{1}{4} [1 - x_0] + \frac{1}{5} \sqrt{z^2 - 1}; \quad z \geq 1, x_0 \leq 1;$$

$$r_1 = \frac{\sqrt{x_0^2 - 1} + \sqrt{z^2 - 1}}{5}; \quad z, x_0 \geq 1.$$

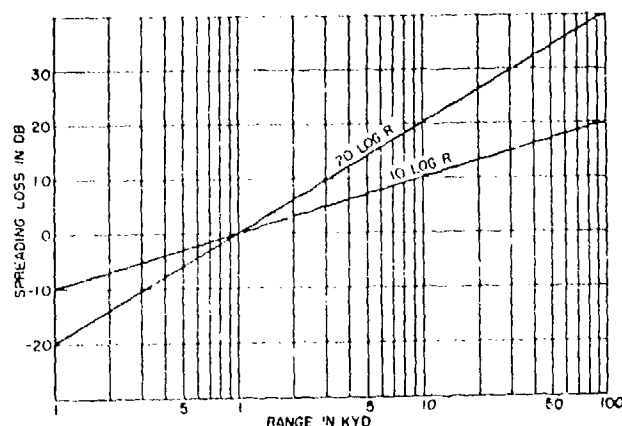


Fig. 2 - Spreading Loss (db)

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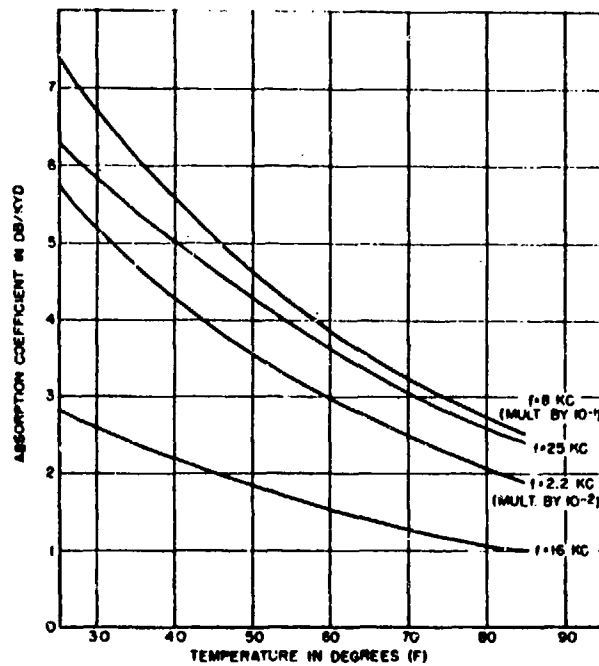


Fig. 3 - Absorption Coefficient (db/kyd)

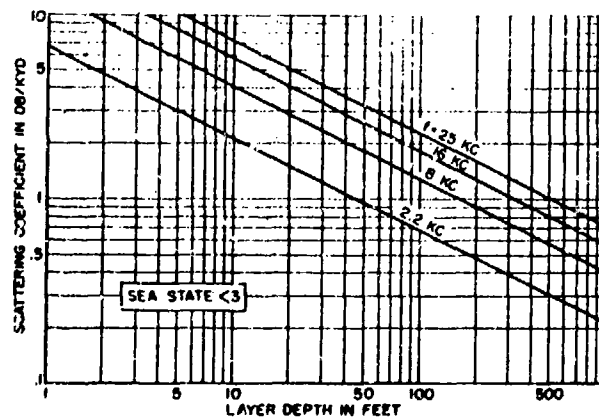


Fig. 4 - Scattering Attenuation Coefficient (db/kyd)

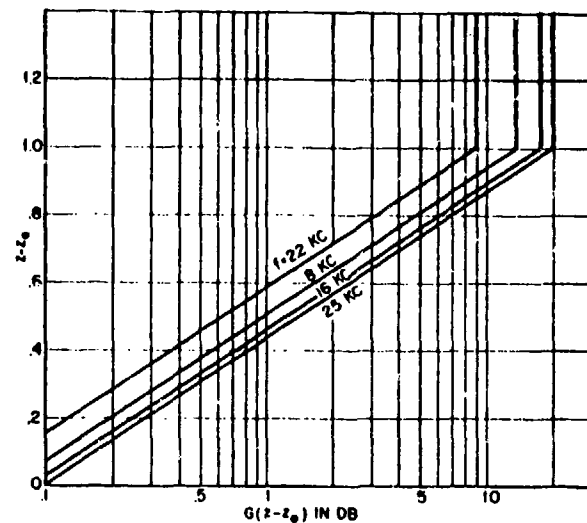


Fig. 5 - First Depth-Loss Factor (db)

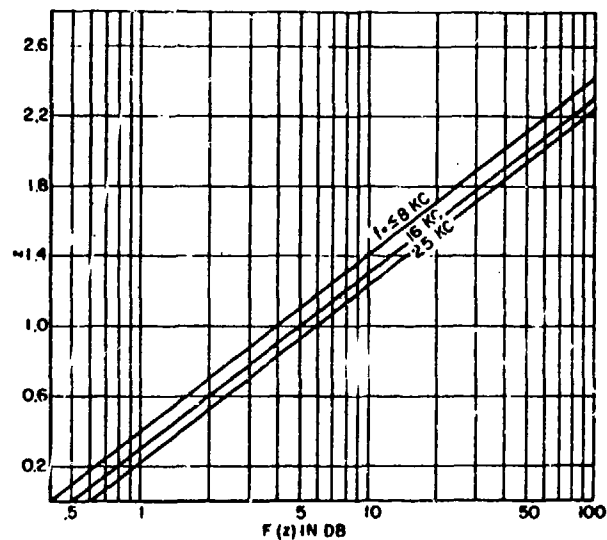


Fig. 6 - Chart for Computing Second Depth-Loss Factor,  $H(z, z_0)$

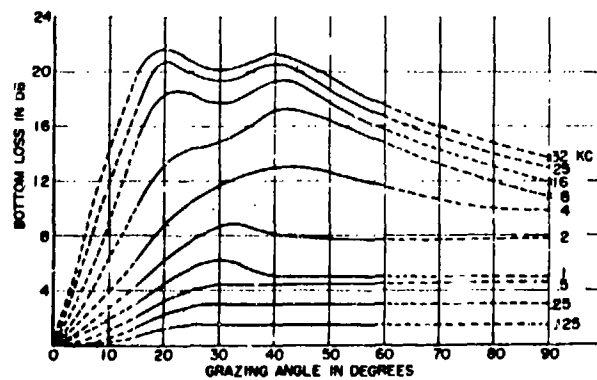


Fig. 7 - Bottom Loss vs. Grazing Angle

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The propagation-loss formulas for the various modes of propagation are the following:

**Direct Radiation Zone (Zone I),  $0 \leq r \leq r_1$**

When both ends of the transmission path lie within or at the bottom of the surface layer, the following formula applies:

$$N_w = 20 \log R + aR + G(z - z_0) \frac{r}{r_1} + 60. \quad (1)$$

At all other times use the smaller of the two transmission losses computed by Formula (1) and the following:

$$N_w = 20 \log R + aR + [25 - \sqrt{|Z - L|} - \sqrt{|Z_0 - L|} + 5R] \left( \frac{f}{25} \right)^{1/3} + 60. \quad (2)$$

The quantity within the parentheses, multiplying the frequency term, is taken as zero when it is not positive.

**Zone of First-Order Surface Reflection and Shadow Zone (Zone II)**

Two propagation modes occur in Zone II:

Energy has been reflected at least once at the surface. The area covered is  $z_0 \leq 1, r_1 \leq r \leq r_1 + \frac{1}{2}$ . Then,

$$N_w = 20 \log R + aR + 2(r - r_1)H(z, z_0) + [1 - 2(r - r_1)]G(z - z_0) + 60. \quad (3)$$

The shadow zone beyond the limiting ray is delineated by

$$z_0 \geq 1, z \geq 1, r_1 \leq r \leq r_1 + \frac{1}{2}.$$

For Zone II use Formula(3) or Formula(2), whichever yields the smaller propagation loss.

**Zone of Second- or Higher-Order Surface Reflection (Zone III)**

Energy has been reflected at least twice at the surface. It covers the area  $z_0 \leq 1, r_1 + \frac{1}{2} \leq r$ . Then,

$$N_w = 10 \log R + (a + a_s)R + H(z, z_0)$$

$$- a_s \sqrt{L} (r_1 + \frac{1}{2})$$

$$+ 10 \log [\sqrt{L} (r_1 + \frac{1}{2})] + 60. \quad (4)$$

The shadow zone beyond the limiting ray is delineated by

$$z_0 \geq 1, z \geq 1, r_1 + \frac{1}{2} \leq r.$$

For Zone III use Formula(4) or Formula(2), whichever yields the smaller propagation loss.

**Transmission Via Depressed Sound Channel**

For this mode, the depths of the source and the receiver are referred to the axis of the channel as the origin, and the channel half-width, equivalent to the layer depth of a surface isothermal layer, is taken to be one-half the depth of the axis. Thus,

$$N_w = 20 \log R + aR$$

$$+ H \left( \sqrt{\frac{2|Z - D|}{D}}, \sqrt{\frac{2|Z_0 - D|}{D}} \right) + 60. \quad (5)$$

**Transmission Via Bottom Reflection**

Transmission takes place by one bottom reflection:

$$N_w = 20 \log R + aR + N_B + 60, \quad (6)$$

where  $R$  is the slant range from the source to the bottom to the receiver for specular reflection and  $N_B$  is the bottom loss for the grazing angle at the point of reflection and is given in Fig. 7.

**ANALYSIS OF DISPERSIONS**

The probable errors of the propagation loss estimated by this method are given below:

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Probable Errors of Propagation-Loss Predictions (AMOS) (±db)

	Frequency (kc)	2.2	8	16	25
Mode of Transmission (Formulas 2 and 5)		6.5	5	6.5	9
Mode of Transmission (Formulas 1, 3, and 4)		4	3	4.5	5
Reciprocal Difference		3.5	2.5	1.5	3.0

These errors result partly from the inadequacies of the method, from basic fluctuations which can not be predicted, and from errors of measurement. In order to estimate the fluctuations, a study has been made of the sound fields measured under identical conditions but with the source and the receiver interchanged. The difference between the two measurements is referred to as a reciprocal difference. Except for that mode of transmission associated with Formulas (2) and (5), the error of estimation is approximately 1-1/2 db greater than the mean reciprocal difference. The probable er-

rors associated with the bottom reflection data (Fig. 7) are given in Fig. 8.

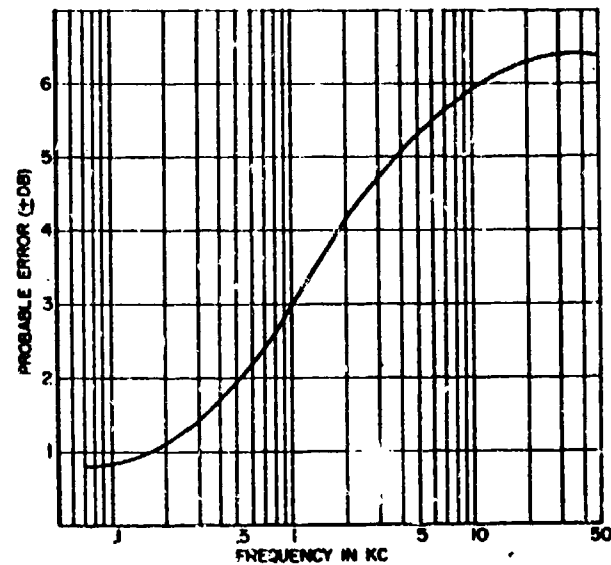


Fig. 8 - Probable Error in Bottom Loss vs. Frequency

### ASSOCIATED COMPUTATIONAL FACTORS FOR PROPAGATION LOSS

In order to compute the individual terms of the propagation modes, the following formulas are required:

Absorption Coefficient (db/kyd)  
(see Fig. 3)

$$a = \frac{A f^2 / T}{f^2 + f_T^2} + \frac{B f^2}{f_T} \quad (7)$$

where

$$A = 0.651, B = 0.0269,$$

$$f_T = 1.23 \times 10^6 - [2100 / (T + 459.6)]$$

$$= 1.23 \times 10^6 \times e^{-4830 / (T + 459.6)},$$

and then

$$A/B = 24.2; f_{50} = 93.$$

For low frequencies,

$$a \sim \frac{0.67 \delta f^2}{f_T}$$

and

$$a_0 \sim 0.0073 f^2 \text{ for } T = 50^\circ \text{ F.}$$

Scattering Attenuation Coefficient  
(db/kyd) (see Fig. 4)

$$a_s = 4.5 \left( \frac{f}{L} \right)^{1/2}, \delta < 3$$

$$= 9 \left( \frac{f}{L} \right)^{1/2}, \delta \geq 3.$$

First Depth-Loss Factor (db)  
(see Fig. 5)

$$G(x - x_0) = 0.1 \times 10^{2.3(x - x_0) / (f/25)^{1/3}}, (x - x_0) \leq 1$$

$$= 20 (f/25)^{1/3}, (x - x_0) \geq 1.$$

Second Depth-Loss Factor (db)  
(computed from Fig. 6)

$$H(x, x_0) = F(x - x_0) + F(x) + F(x_0),$$

where

$$F(x) = 0.4 \times 10^3 \left( \frac{f}{8} \right)^{1/3}, f \geq 8;$$

$$= 0.4 \times 10^3, f \leq 8.$$

## STUDY B

### CONTOURS OF TRANSMISSION LOSS FOR STANDARD CONDITIONS AND CORRECTION CHARTS<sup>1</sup>

by

M. R. Powers, K. R. Dickson, and L. P. Onyx

#### INTRODUCTION

Contours of standard transmission loss,  $N_{\theta\theta}$ , have been plotted for ten frequencies and three projector depths, for a standard temperature (50° F.) and a standard layer depth (100 feet). Correction charts have been plotted for each frequency for the correction required because of changes in layer depth, temperature, and sea state. Values of the absorption coefficient,  $\alpha$ , for various temperatures are also included. The corrections are to be added to the standard transmission loss. The loss contours and correction charts for each frequency have been grouped together for ready reference.

#### METHOD OF COMPUTATION

The values of the transmission loss first were computed from Formulas (1), (3), and (4) of Study A. In all the computations a layer depth of 100 feet, a temperature of 50° F., and a sea state of less than 3 were assumed. Computations were made for projector depths of 20, 50, and 100 feet, for frequencies of 2, 10, and 25 kc.<sup>2</sup> For each projector depth and frequency, the standard transmission loss was computed at seven receiver depths and eight ranges. These values were used to plot contours of constant loss. Examples of such contours are given in Figs. 1A through 1C, 3A through 3C, and 5A through 5C.

A plot of transmission loss for Formula (2) of Study A was also made for each frequency. The

loss was computed as a function of  $\Sigma$ , where

$$\Sigma = \sqrt{|Z - L|} + \sqrt{|Z_0 - L|}.$$

The curves were plotted for constant range,  $R$ , between 0.5 and 25 kyd, for values of  $\Sigma$  from 0 to 140. These curves should be used when they give a smaller loss value than the value computed from Formulas (1), (3), and (4) of Study A but can not be used when both the projector and the receiver are above the layer. Examples of these computations are given in Figs. 1D, 3D, and 5D.

The layer-depth correction was computed from the formula:

$$\Delta_L = 10 \log \frac{L}{L_0} - \alpha_0 R \left( \frac{\sqrt{L_0}}{\sqrt{L}} - 1 \right),$$

where

$L$  = layer depth (ft),

$L_0$  = standard layer depth = 100 ft,

$\alpha_0$  = absorption coefficient (db/kyd) at  
 $T = 50^\circ \text{ F.}$ , and

$R$  = range (kyd).

This formula was evaluated for twelve values of  $L$  between 9 and 1024 feet. Curves were plotted for  $\Delta_L$  versus  $R$ , for constant  $L$ . The contours of constant  $\Delta_L$  (see Figs. 2, 4, and 6) were plotted by interpolating in these curves. This correction applies to Formulas (1), (3), and (4) of Study A.

In order to find the transmission loss for a given  $R$ ,  $Z$ , and  $Z_0$ , for a layer depth different from 100 ft, it is necessary to find the values of the scaled variables  $r$ ,  $x$ , and  $x_0$  by using the actual layer depth. The standard loss contours are entered with  $r$ ,  $x$ , and  $x_0$ , and the value of  $N_{\theta\theta}$  is read. The correction term is found from the layer correction contours, where these curves are entered with  $R$  and  $L$ .

<sup>1</sup> This report, together with a complete set of working charts, appeared originally as USL Technical Memorandum No. 1110-101-54, 17 August 1954 (UNCLASSIFIED).

<sup>2</sup> The original computations were made at additional frequencies of 1, 5, 8, 12, 14, 20, and 31 kc. However, the computations for the 1-kc frequency are extrapolated from data at higher frequencies and thus are to be considered as estimates only.

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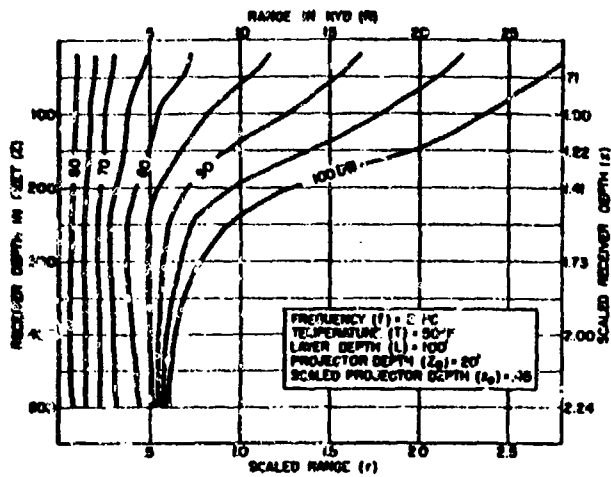


Fig. 1A

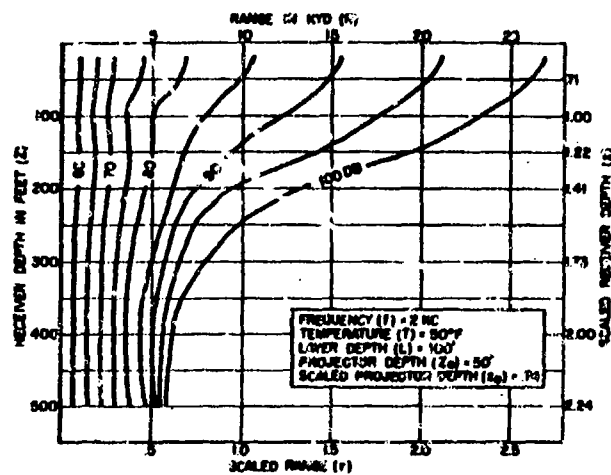


Fig. 1B

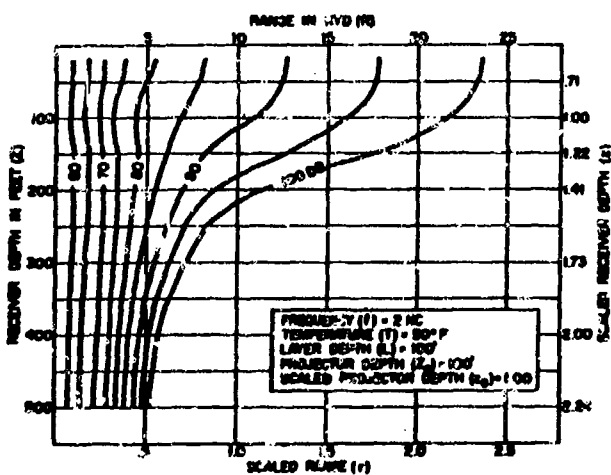


Fig. 1C

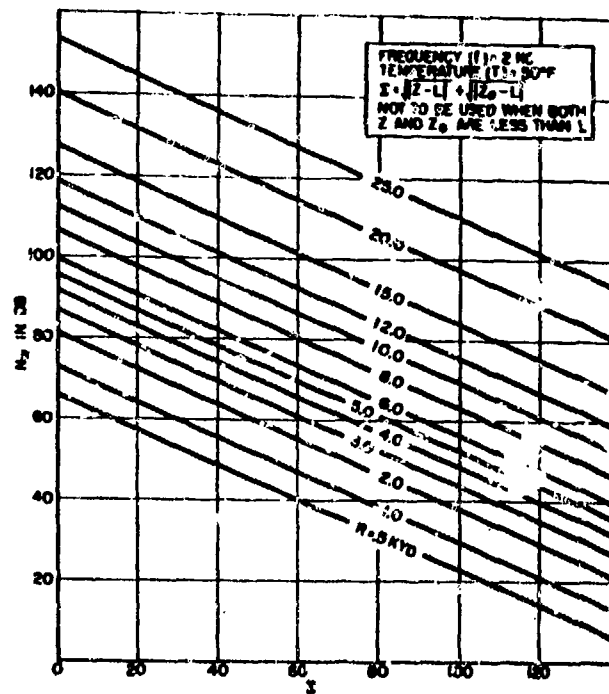


Fig. 1D

Fig. 1 - Propagation-Loss Contours  
(in db for 2-kc frequency)

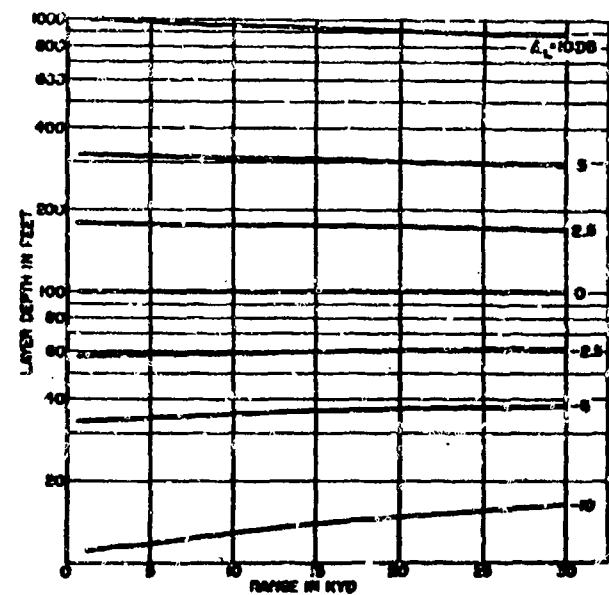


Fig. 2 - Layer-Depth Convexion Contours (2 kc)

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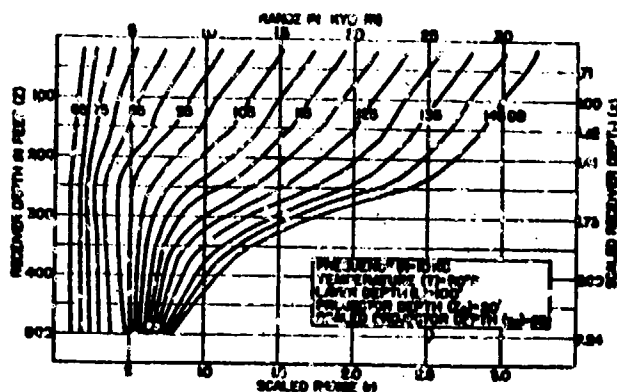


Fig. 3A

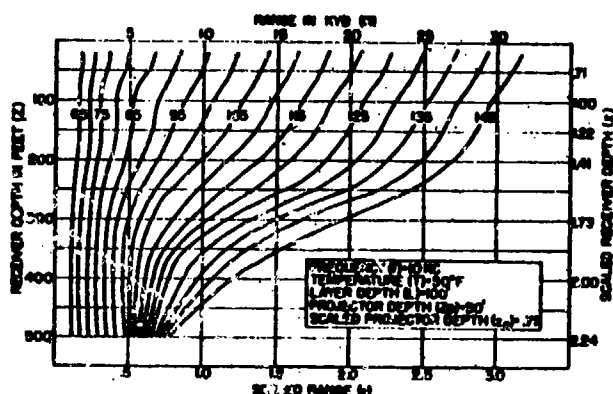


Fig. 3B

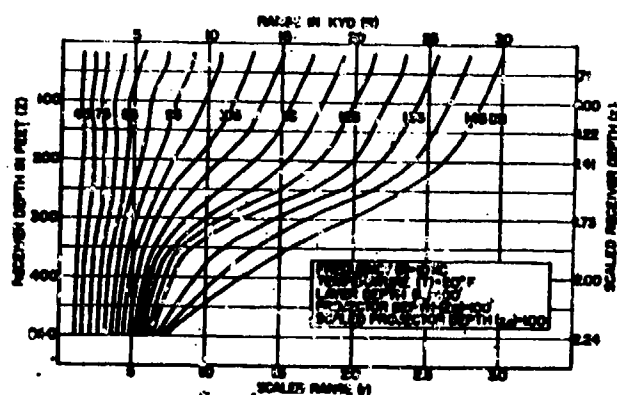


Fig. 3C

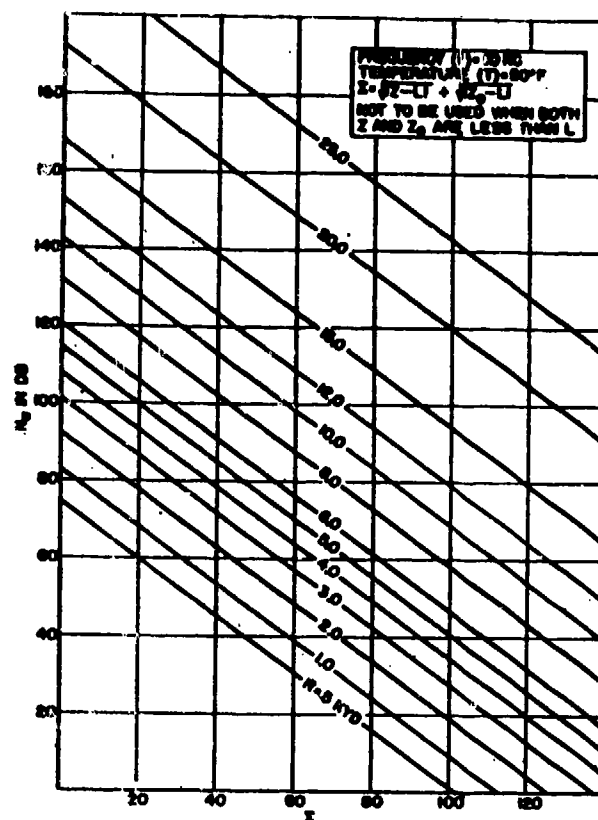


Fig. 3D

Fig. 3 - Propagation-Loss Contours (in db for 10-kc frequency)

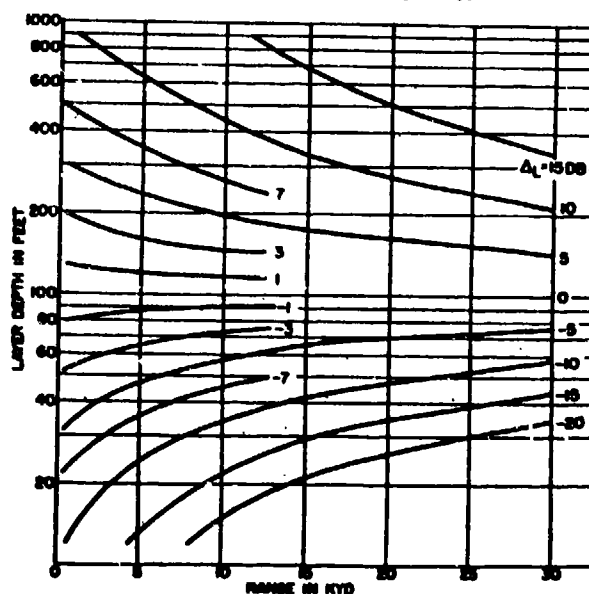


Fig. 4 - Layer-Depth Correction Contours (10 kc)



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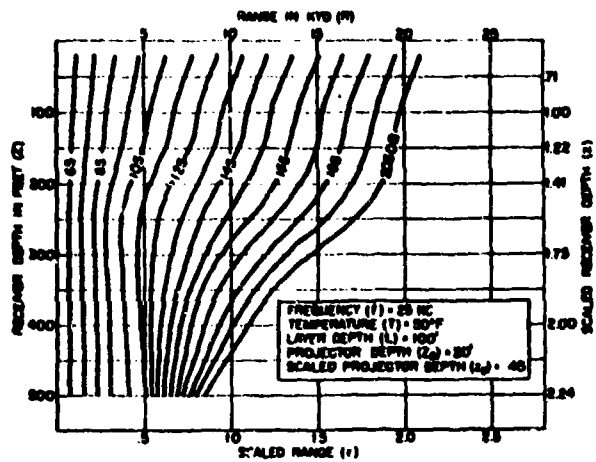


Fig. 5A

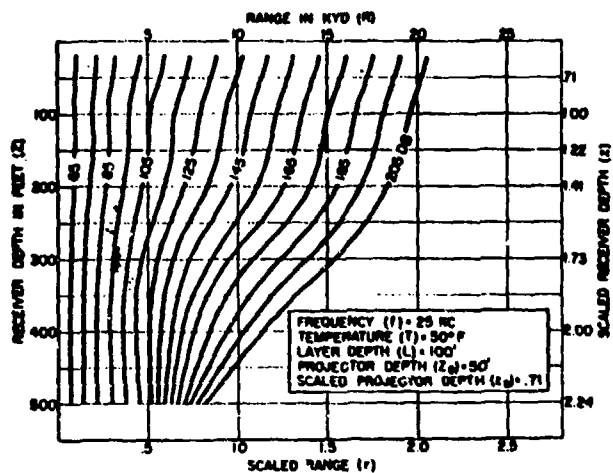


Fig. 5B

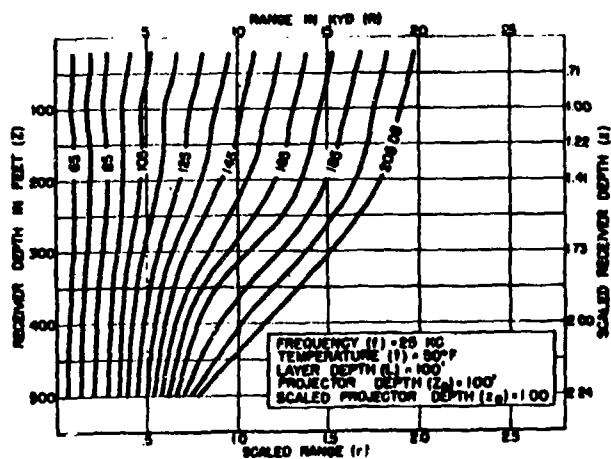


Fig. 5C

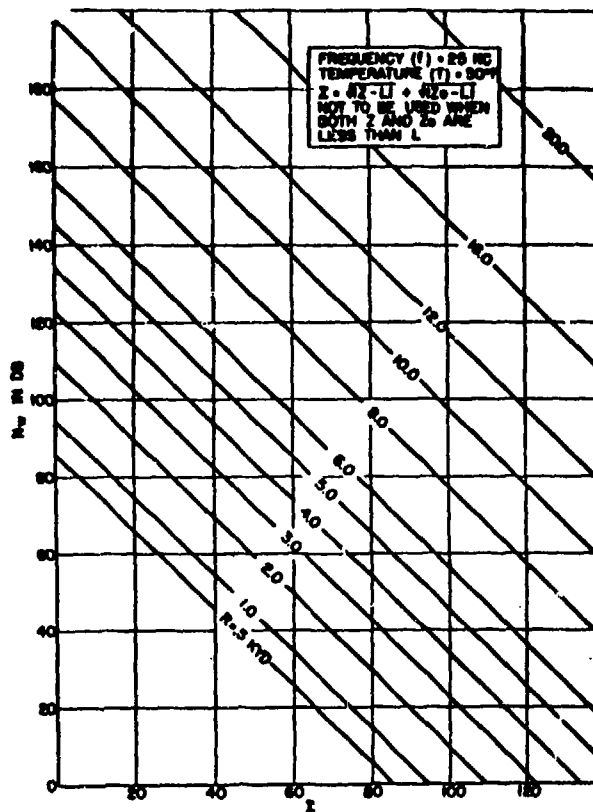


Fig. 5D

Fig. 5 - Propagation-Loss Contours (in db for 25-kc frequency)

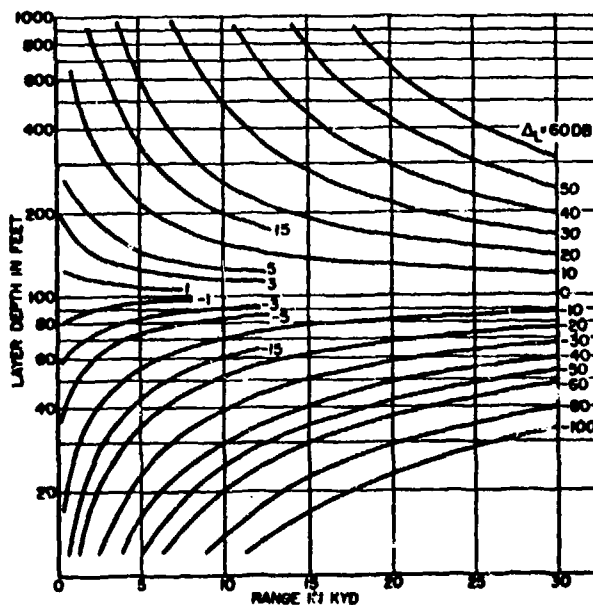


Fig. 6 - Layer-Depth Correction Contours (25 kc)

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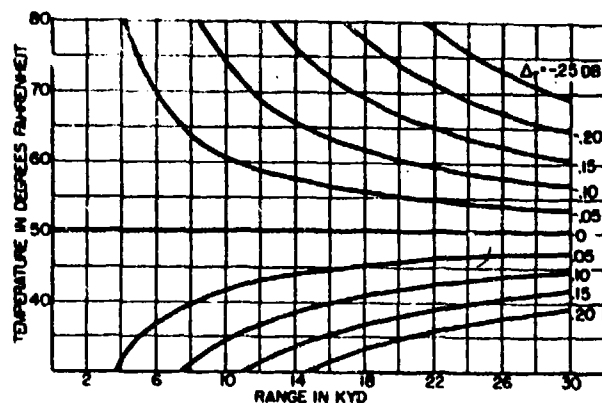


Fig. 7A - 2 kc

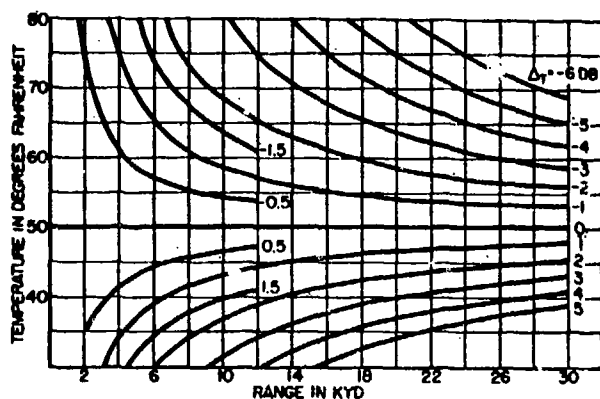


Fig. 7B - 10 kc

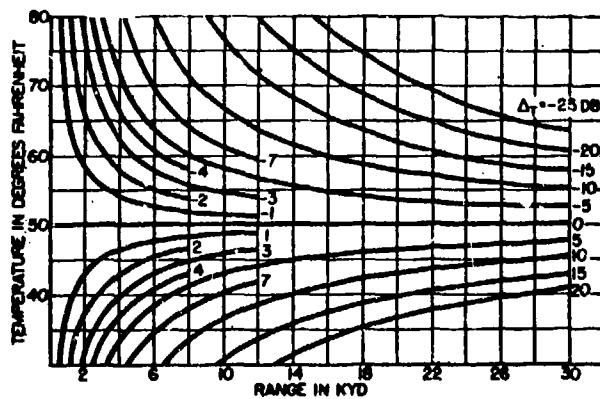


Fig. 7C - 25 kc

Fig. 7 - Temperature Correction Contours  
(2 kc, 10 kc, and 25 kc)

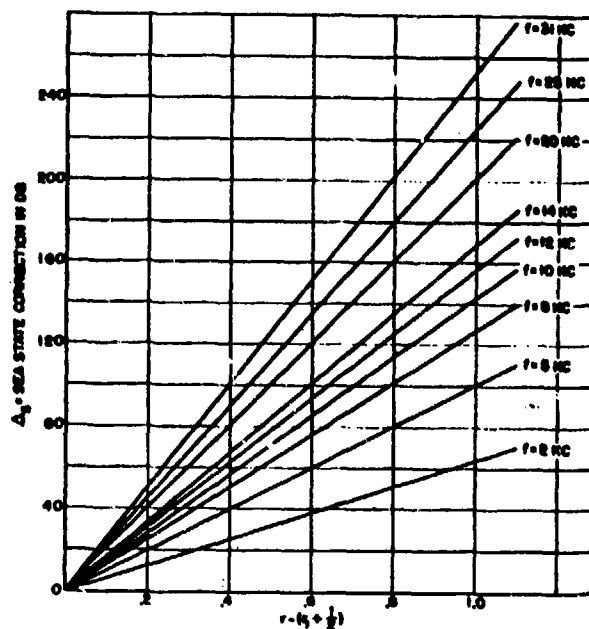


Fig. 8 - Sea-State Correction (for Sea State 3 or Greater)

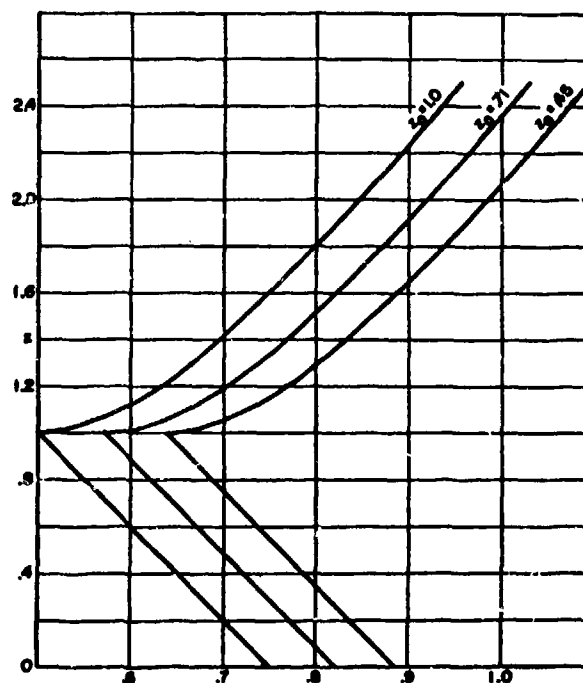


Fig. 9 - Scaled Range in Propagation Zone III vs. Depth

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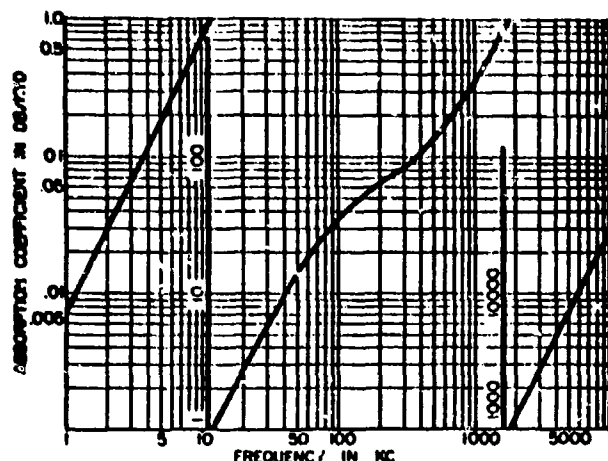


Fig. 10 - Absorption Coefficient (in db/kyd) vs. Frequency (in kc) for  $T = 50^{\circ} \text{ F.}$

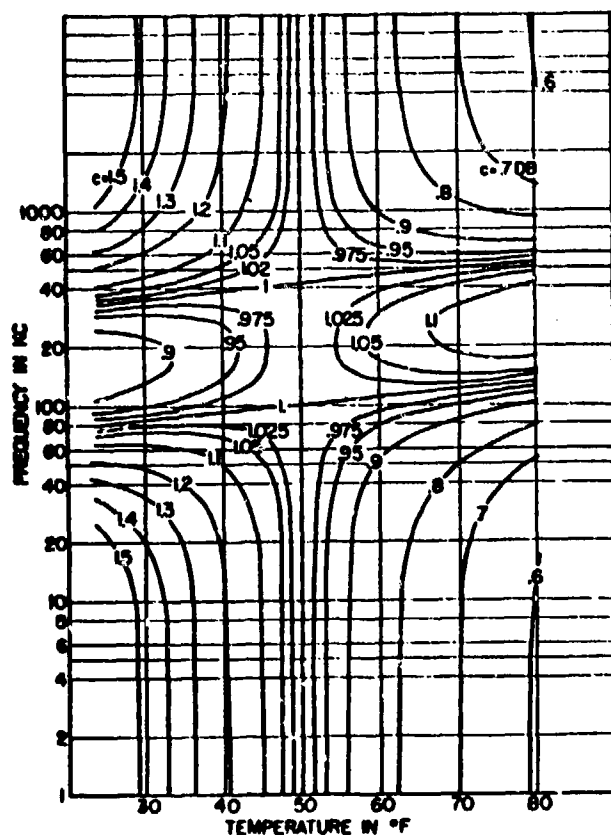


Fig. 11 - Temperature Dependence of Absorption Coefficient Ratio ( $c = a/a_0$ ) ( $a_0$  = Absorption Coefficient at  $50^{\circ} \text{ F.}$ )

The temperature correction contours were plotted in a manner similar to that used for the layer correction:

$$\Delta_T = a_0 R \left( \frac{a}{a_0} - 1 \right),$$

where

$a$  is evaluated at temperature =  $T^{\circ} \text{ F.}$ ,

$a_0$  is evaluated at standard temperature =  $50^{\circ} \text{ F.}$ , and

$R$  is range (kyd).

The formula was evaluated for six values of  $T$  between  $30^{\circ}$  and  $90^{\circ}$ , and the curves were plotted for  $\Delta_T$  versus  $R$  at a constant  $T$ . The contours of constant  $\Delta_T$  (see Figs. 7A, 7B, and 7C) were plotted by interpolating in these curves. This correction applies to all propagation zones.

It should not be assumed that interpolation in these correction charts will be accurate for an interval smaller than one-half the interval between contours. If greater accuracy is desired, the correction values should be found from the formulas or from graphs for constant  $L$  or  $T$ . This is particularly true for ranges of less than one kiloyard.

The sea-state correction

$$\Delta_s = 4.5 / V^2 [r - (r_1 + 1/2)]$$

has been plotted for each frequency (Fig. 8). This is applicable only for the ranges  $r \geq r_1 + 1/2$ , for which Formula (4) of Study A applies. These ranges may be determined by using Fig. 9 for the three values of projector depth ( $z_0 = 0.45, 0.71, 1.00$ , or  $Z_0 = 20, 50, 100$  feet).

Figure 10 gives the values of  $a_0$  for frequencies from 1 to 10,000 kc, at  $T = 50^{\circ} \text{ F.}$  The values of  $c = a/a_0$  are plotted for temperatures from  $25^{\circ}$  to  $80^{\circ} \text{ F.}$  and for frequencies from 1 to 10,000 kc (Fig. 11).

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## STUDY C

### ERROR STUDY OF AMOS PROPAGATION-LOSS ANALYSIS

by  
W. H. Thorp

An investigation was made of the magnitude of errors to be expected from the use of the analytical formulas given in Study A of this report for the estimation of propagation loss. This was done by working with a representative sample of the entire data file. This sample was obtained by selecting at random a single IBM card to represent each of the North Atlantic deep-water stations which were occupied between 1949 and 1953. Each card so selected contained the measured values of propagation loss for one or more of the four discrete acoustic frequencies (2, 2, 8, 16, and 25 kc) for a given range and projector-receiver depth pair. These data are listed in Table 1.

The mode of propagation which applied to each particular station card was determined from a consideration of the pertinent parameters as indicated in Study A. The corresponding values of propagation loss were then computed from the formulas of Study A. It should be noted that more than one propagation mode may apply under the transmission conditions; therefore, calculations using each applicable formula must be made and the result which indicates the least loss must be chosen. This, in effect, increases the numerical effort required by about 50%.

In Table 2 are presented the probable errors of the prediction method obtained by subtracting the

computed values of propagation loss from the measured values for the indicated propagation modes for the 149 stations of Table 1. For the remaining nine stations, the prevailing propagation mode appeared to be by way of the ocean bottom.

The magnitude of the probable errors reflects some of the time variability of the ocean itself as a propagation medium. This effect was estimated in this study by considering the reciprocal nature of propagation over the same path with transmitting and receiving positions interchanged within a period of from 15 to 20 minutes for most of the stations in Table 1. The reciprocal differences referred to in Table 2 are the differences in measured propagation loss over the same path, but with receiver and projector positions interchanged. It may be seen that a sizable part of the probable error of estimation arises from the time variability introduced by the ocean. These errors appear to be independent of range over the ranges of the AMOS experiments (1 to 25 kyd).

It may be seen that the probable errors for the downward refraction mode of propagation appear to be larger than those associated with surface channel propagation. The errors associated with propagation by way of the bottom are treated separately in Study D.

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Table 1 (Cont'd)

Cruise	Station	Layer Depth (ft)	Sea State	Surface Temperature (°F.)	Projector Depth (ft)	Receiver Depth (ft)	Range (yd)	Propagation Formula*	2.2 kc		8 kc		16 kc		25 kc	
									N <sub>W</sub>	N <sub>NE</sub>	N <sub>W</sub>	N <sub>NE</sub>	N <sub>W</sub>	N <sub>NE</sub>	N <sub>W</sub>	N <sub>NE</sub>
5	22	25	1	70.0	20	175	8,000	(6)			107	103	131	115		
	23	0	1	70.0	50	450	7,670	(2)			99	103	108	117	126	117
	24	50	1	71.0	250	950	5,300	(2)			81	89	84	97	98	110
	25	100	3	69.0	250	350	2,720	(2)			66	77	72	81	81	88
7	2	75	1	76.0	20	500	4,680	(3)			90	81	85	96	97	96
	3	125	2	79.9	200	400	7,900	(4)							115	119
	5	0	2	81.5	100	400	4,140	(2)							113	99
	6	175	2	81.0	20	20	7,950	(3)			80	81	94	88	126	101
8	7	280	3	81.0	100	400	7,750	(3)			85	86	100	97	120	107
	8	260	2	73.5	50	100	4,000	(3)			61	74	78	77	79	84
	1	480	3	68.0	50	150	5,220	(1)			79	77	81	82	82	92
	2	350	2	68.8	50	100	5,080	(1)			94	71	99	74	82	80
9	3	390	2	69.2	450	450	12,000	(4)			106	78	102	89	137	100
	4	380	2	68.8	250	500	2,720	(1)			81	69	61	73	84	78
	7	440	2	67.1	150	450	8,100	(3)			91	85	97	94	111	110
	8	550	1	64.9	50	425	6,620	(3)			83	84	93	93	100	107
10	9	0	1	61.4	20	200	1,520	(2)			65	73	65	78	65	83
	10	0	1	63.3	20	425	5,150	(2)			76	94	83	103	92	110
	11	0	1	60.4	20	100	8,770	(6)			79	95	87	112	106	133
	12	190	3	55.6	20	425	880	(2)			61	61	64	61	85	64
11	13	260	2	60.1	50	350	5,800	(3)			87	82	91	90	106	103
	14	200	2	58.5	350	400	5,140	(3)			71	89	91	98	92	112
	15	340	2	57.0	50	250	2,860	(1)			70	71	69	75	77	82
	16	500	1	56.8	400	450	4,850	(3)			75	78	84	85		
12	17	20	1	58.2	100	100	20,200	(6)			93	103				
	18	45	2	57.0	20	100	8,300	(4)			94	102	105	119	120	143
	19	300	3	53.0	20	450	7,800	(3)			76	73	91	107	107	127
	20	50	3	52.4	20	50	4,950	(4)			76	84	87	94	98	105
13	21	100	2	52.4	150	400	17,400	(4)			94	104				
	22	65	2	56.0	20	50	18,150	(4)			103	112				
	23	120	2	65.9	20	100	12,200	(4)			95	92	113	112	133	149
	24	90	2	56.4	20	250	8,440	(3)			79	105	86	124	115	135
14	25	110	3	66.8	100	200	17,900	(6)			98	113				
	26	40	1	66.1	20	50	17,900	(6)			99	113				
	1	15	1	59.5	50	200	2,600				85	82	88	80	102	95
	3	30	1	55.0	50	100	2,960	(7)	64	75	73	76	75	82	99	89
15	4	125	3	57.8	150	350	4,100	(5)			76	81	77	88	94	124
	5	100	3	51.0	450	450	7,700	(5)			94	88	101	101	119	121
	6	50	2	49.8	100	200	3,200	(5)			87	81	85	88	104	90
	7	40	1	50.8	50	100	8,220	(4)			106	75				
16	8	60	1	50.5	150	250	4,600	(2)			96	93	105	103	134	110
	9	55	2	54.0	50	150	8,080	(6)	96	88	113	99				
	10	85	1	58.5	50	350	4,640	(3)			85	99	103	119	126	124
	11	75	1	66.0	95	260	1,530	(1)	80	68	79	69	82	83	100	76
17	12	100	1	68.0	50	450	3,220	(1)							120	95
	13	100	1	70.0	50	200	3,260	(3)	93	73	97	75	99	80		
	14	40	2	68.0	30	150	3,500	(5)			93	87	104	94	129	194
	15	75	2	66.9	100	350	18,200	(5)	98	97						
18	16	115	3	63.8	250	450	8,730	(4)			104	70				
	17	125	2	62.5	250	400	1,700	(1)			60	66	65	69	70	71
	18	80	2	59.0	100	350	8,400	(5)			113	94				
	1	200	2	50.0	50	200	2,950	(3)			65	75	75	74	81	85
10	2	18.9	4	41.0	250	350	5,150	(1)			76	77	92	86	102	100

\* From Study A.

(Continued)

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Table 1 (Cont'd)

Cruise	Station	Layer Depth (ft)	Sea State	Surface Temperature (°F.)	Projector Depth (ft)	Receiver Depth (ft)	Range (yd)	Propa- gation Formula	2.2 kc		8 kc		16 kc		25 kc	
									N <sub>w</sub>	N <sub>wo</sub>	N <sub>w</sub>	N <sub>wo</sub>	N <sub>w</sub>	N <sub>wo</sub>	N <sub>w</sub>	N <sub>wo</sub>
10	3	895	1	43.9	30	150	5,750	(1)			81	79	93	88	103	103
	4	1045	3	43.6	250	475	4,580	(1)			76	76	90	83	98	96
	5	1625	1	47.2	50	250	740	(1)			60	58	65	57	66	61
	6	1410	2	48.8	500	500	5,450	(1)			76	77	91	85	100	99
	7	1500	2	48.7	30	100	3,280	(1)			73	72	82	77	85	85
	8	1055	4	45.1	250	300	6,500	(1)			82	80	95	90	108	107
	9	300	2	37.7	100	150	3,320	(3)	68	71	74	73	94	90	95	88
	10	330	3	43.1	50	475	4,730	(1)	62	77	78	81	70	65	107	103
	11	650	3	47.3	50	150	1,340	(1)	65	63	61	63			69	69
	13	580	4	53.3	50	100	2,710	(1)	69	69					83	80
	15	55	1	39.1	250	250	3,800	(5)	72	81	84	83	76	90	84	100
	16	200	2	58.3	30	300	4,380	(3)	67	73	79	75	86	80	100	90
	17	65	2	59.9	30	50	3,850	(3)	69	76	77	77	83	83	96	92
	18	165	2	40.1	400	500	3,200	(3)			75	75	87	81	92	90
11	1	0	1	52.5	50	500	1,020	(2)			56	61	61	62	83	65
	2	75	2	47.5	150	250	2,750	(2)			73	79	79	86	89	95
	3	70	2	44.3	100	250	4,200	(5)	84	79				114	102	
	4	69	2	46.2	250	475	5,290	(5)	73	81	71	83	81	95	99	106
	5	65	1	49.0	150	500	2,660	(2)	60	73	70	76	73	80	81	89
	6	0	1	50.4	250	475	4,740	(2)	71	79	74	84	79	91	90	105
	7	20	1	50.8	50	450	5,310	(2)			80	93	94	106	113	123
	8	15	1	50.0	20	475	5,890	(6)	85	85	96	95	110	110	134	131
	9	0	1	50.0	150	350	3,100	(2)	80	75	79	78	89	83	97	93
	10	0	2	44.5	100	475	5,530	(2)	85	85				118	122	
	11	0	1	49.1	20	250	6,180	(6)	95	89	104	103				
	12	25	1	37.0	50	400	7,400	(6)	107	87	108	98	110	115	141	142
	13	0	1	39.0	200	500	5,540	(2)	89	83	87	89	101	101	120	119
	14	0	1	39.2	100	475	2,840	(2)	67	73	74	76	81	81	92	91
	15	40	2	52.0	20	250	18,000	(6)	95	93	107	108				
	16	50	1	52.5	250	350	5,600	(2)	81	85	93	93	105	103	120	119
	17	85	3	50.7	50	350	18,200	(6)	101	94	113	109				
12	18	90	1	58.8	150	500	2,550	(2)	82	73	84	76	84	70	112	87
	20	50	2	67.3	100	300	3,120	(2)	83	78	91	83	100	89		
	2	255	2	62.0	20	500	3,020	(1)							92	94
	4	900	3	63.2	103	253	8,310	(3)	81	80	75	81	104	93	117	110
	5	800	3	64.8	30	478	0,200	(3)	78	80	82	83	88	92	107	109
	6	30	2	71.9	20	503	5,480	(6)			89	105	99	133		
	7	0	2	78.5	20	290	8,840	(6)			94	109				
	8	580	3	75.2	20	251	8,760	(3)			94	84	108	93	93	109
	9	280	3	76.0	101	251	12,460	(4)			96	94				
	10	270	2	76.1	404	505	3,680	(3)	67	75	76	76	85	80	97	66
	11	120	3	77.7	98	251	3,080	(3)			75	73	81	77	86	82
	12	0	2	80.5	48	50	17,600	(6)	72	91	90	107				
	13	120	3	78.9	248	448	3,090	(3)	65	75	77	77	81	82	89	87
	14	30	2	79.2	20	52	8,420	(4)			81	99		101	135	
	15	100	2	77.3	20	20	7,720	(3)	61	81	75	82	88	90	114	105
	16	135	1	71.2	20	50	3,500	(3)	51	71				77	83	
	17	50	3	77.5	50	102	7,680	(4)	76	81						
	18	0	2	74.2	109	475	3,560	(2)	82	73	59	80	62	84	74	92
	19	0	2	75.5	70	51	18,140	(6)	81	96	96	115				
	20	100	2	71.0	41	500	7,800	(5)	75	85			93	97	123	112
	21	150	2	67.0	232	250	7,960	(3)					72	109		
	22	180	2	57.0	249	471	8,110	(5)	87	87	95	85	107	100	134	117

\* From Study A.

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Table 2

PROBABLE ERRORS OF PROPAGATION-LOSS PREDICTIONS (AMOS) ( $\pm$ db)				
	2.2 kc	8 kc	16 kc	25 kc
Mode of Transmission (Formulas 2 and 3, Study A)	6.5	5.0	6.5	9.0
Mode of Transmission (Formulas 1, 3, and 4, Study A)	4.0	3.0	4.5	5.0
Reciprocal Differences	3.5	2.5	1.5	3.0

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## STUDY D

### TRANSMISSION BY WAY OF THE BOTTOM

by  
M. Schulkin and W. H. Thorp

#### INTRODUCTION

The deep-water bottom-reflection data available as of January 1954 have been assembled in a form which is suitable for use in sonar range predictions. No attempt is made to explain the data; rather, the data are described in terms of a model. The model used is that of propagation by way of the specular path, including an empirical loss at the bottom. At grazing angles approaching  $0^\circ$ , the behavior of the Rayleigh reflection coefficient is assumed. At perpendicular incidence, scattering coefficients deduced from AMOS vertical sounding measurements at 2, 8, and 34 kc were used.

The most extensive sources of bottom-reflection data in deep water for the 2- to 25-kc frequency range are AMOS Cruises NINE, ELEVEN, and TWELVE. Cruises NINE and ELEVEN were notable for their shallow surface sound channels and low, direct acoustic fields at short ranges. As continuous-wave sources were used on these two cruises, the sound energy could arrive by various paths, and some discretion had to be used in selecting data which arrived by way of the bottom. For this purpose, the depth of the isothermal layer, the decrease of the propagation-loss anomaly with range, the constancy of the field with depth, the magnitude of the propagation loss, and the acoustic frequency were all considered. On Cruise TWELVE pulses were used with the result that it was fairly easy to distinguish energy coming via the bottom. Propagation conditions were generally good during this cruise, however, and because only those signals which were less than 40 db below the direct signal could be detected, data were limited to a few stations.

All the AMOS data were assembled into median values, and the bottom loss was plotted against the bottom grazing angle in 5-degree intervals and out to 55 degrees as shown in Fig. 1. The geomet-

rical path was used together with the temperature-dependent absorption coefficients presented in Study A in reducing the propagation-loss values to "bottom loss."

In order to carry the bottom-reflection analysis down in frequency, underwater siren runs from

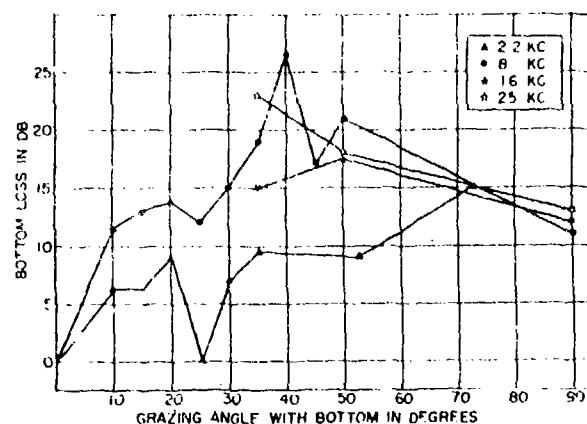


Fig. 1 - Bottom-Loss Data from AMOS Cruises NINE, ELEVEN, and TWELVE

AMOS Cruises ELEVEN and TWELVE were used. Data were considered in frequency bands centered about 1 kc, 2 kc, and 8 kc. Here again judgment had to be exercised in distinguishing bottom reflections, since the source emitted continuously. Bottom-reflection data, obtained by the Naval Electronics Laboratory during 1950 and 1951, were also available for discrete source runs at 500 cps and 1000 cps.<sup>1</sup> The medians for the siren and NEL runs are shown in Fig. 2. The number of runs going into these medians are as follows:

<sup>1</sup> These runs are described by T. P. Condon and R. W. Schillereiff in "Long Range Sound Transmission with a Shallow Towed Source at 500- and 1000-cps Frequency," NEL Report 323, 16 October 1952 (CONFIDENTIAL).



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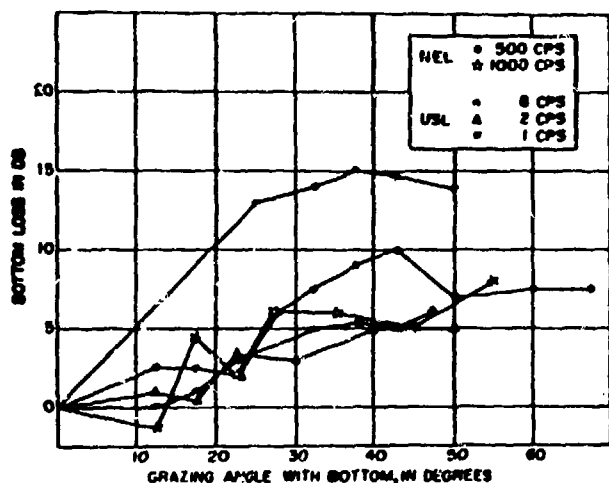


Fig. 2 - Bottom-Loss Data from NEL Discrete Source and USL Siren

a. AMOS Underwater Siren—5 runs at 1 kc, 4 runs at 2 kc, 3 runs at 8 kc.

b. NEL Discrete Source—4 runs at 1 kc and 6 runs at 500 cps.

Finally, bottom-reflection data<sup>2</sup> obtained by the Woods Hole Oceanographic Institution at frequencies below 1 kc through bomb drops were derived for multiple-hop levels for energy lying between the limiting ray and the critical angle. In working out the data, all possible differences in level were used from the WHOI plots of level versus  $R/N$ , where  $R$  is the range and  $N$  is the order of reflection. Values of  $N$  from 1 to 9 were used. The median values of the resulting data are plotted in Fig. 3.

These three sets of data were studied for frequency dependence by plotting median bottom-reflection loss against frequency for the overlapping grazing angle intervals, 10° to 30°, 20° to 40°, and 30° to 50°. The results are shown in Figs. 4A, 4B, and 4C. In drawing smooth curves through the points, the AMOS data were given the greatest weight whenever a question arose. The source of the data is indicated by a letter W for WHOI, N for NEL, S for Siren (AMOS), and A for AMOS.

Plots of bottom loss versus grazing angle then were made, starting at 125 cps and progressing in octave steps. These are presented in Fig. 5. A

<sup>2</sup> See C. B. Officer and J. B. Hersey, "Sound Transmission from Deep to Shallow Water," WHOI Ref. 53-32, August 1953 (SECRET).

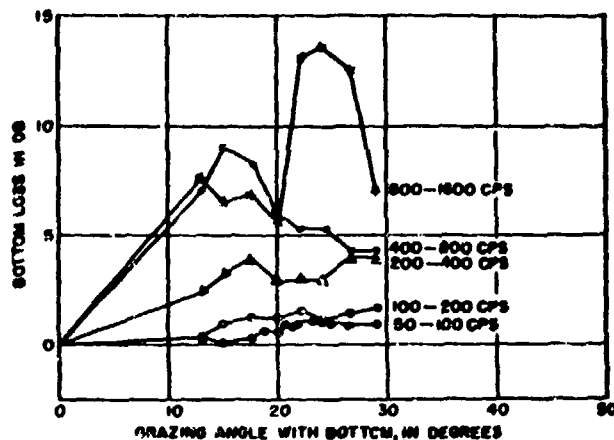


Fig. 3 - Bottom-Loss Data from WHOI Bomb Drops

plot was also made at 25 kc for convenience. The points at 90° (vertical incidence) were obtained from a previous analysis<sup>3</sup> of the AMOS vertical reverberation and bottom-reflection experiments. The pulse-length dependence shown in the study indicates a tendency toward a leveling off at lower bottom-loss values with greater pulse lengths. The pulse data of AMOS Cruise TWELVE also shows a tendency toward lower levels for shorter pulses (i.e., 1/2 sec as compared with 1 sec).

Probable errors of the points about the curves in Figs. 4A, 4B, and 4C were computed and combined with the probable errors of the plots in Figs. 1, 2, and 3 in order to obtain the over-all probable-error curve versus frequency shown in Fig. 6. Finally, a plot of transmission loss versus horizontal range is presented in Fig. 7 for an average water depth of 2000 fathoms and average water temperature of 38° F. for the four frequencies indicated.

### THEORETICAL COMPUTATIONS

Theoretical computations on the basis of two simple models were made in order to observe some dependencies of reflection coefficient on bottom property and bottom structure. In one case consider plane acoustic waves in one infinite, homo-

<sup>3</sup> See D. L. Cole, J. F. Kelly, and A. W. Dartnall, "Vertical Reverberation and Bottom Strength Measurements - Event SIX - Project AMOS," USL Technical Memorandum No. 1110-014-53, 15 May 1953 (CONFIDENTIAL).

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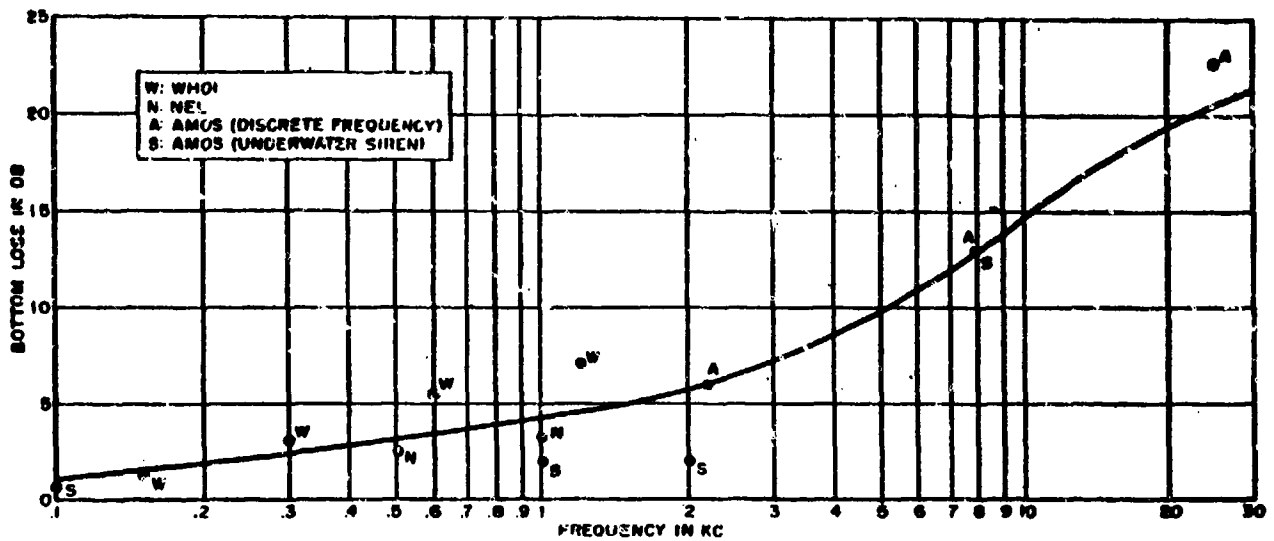


Fig. 4A -  $10^\circ \leq \theta_B \leq 30^\circ$

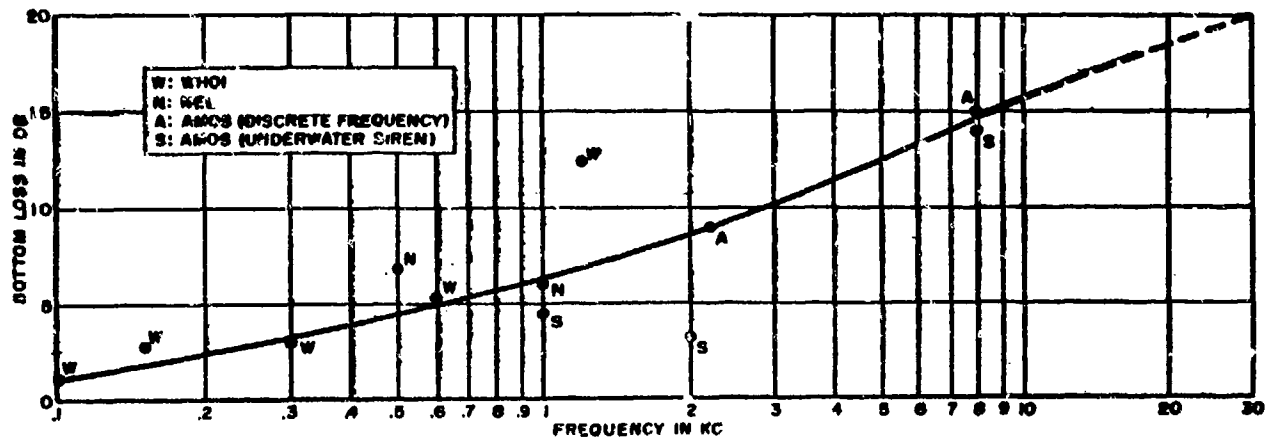


Fig. 4B -  $20^\circ \leq \theta_B \leq 40^\circ$

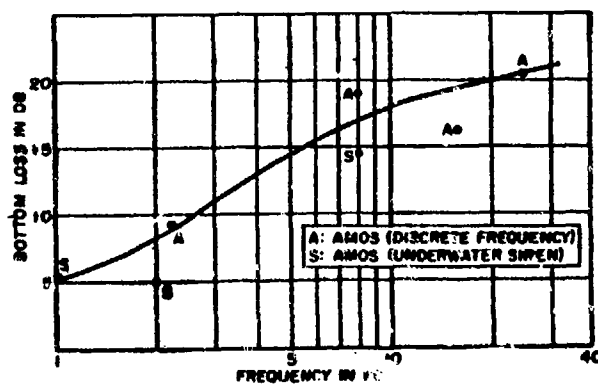


Fig. 4C -  $30^\circ \leq \theta_B \leq 50^\circ$

Fig. 4 - Bottom Loss vs. Frequency

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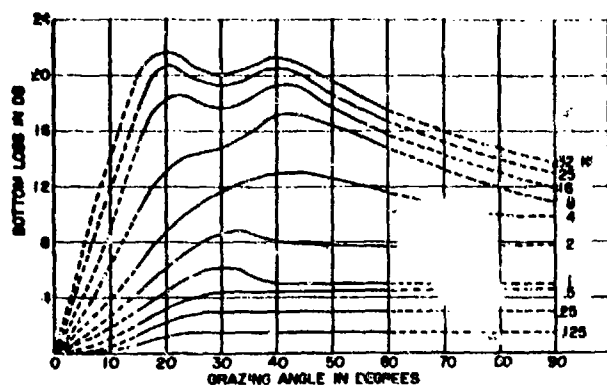


Fig. 5 - Bottom Loss vs. Grazing Angle

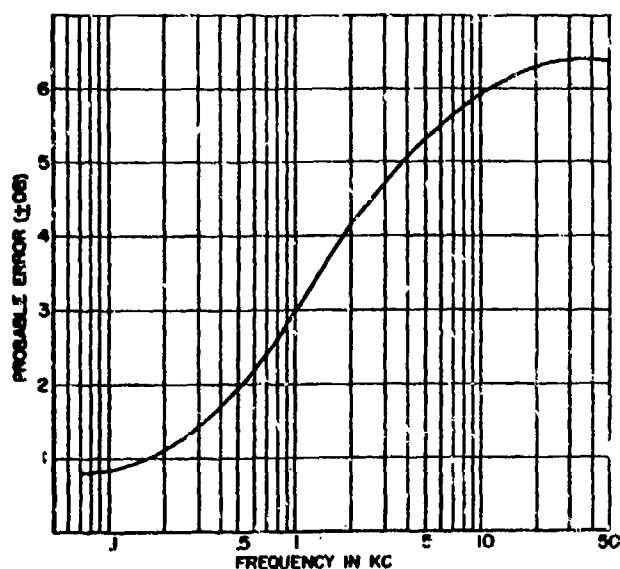


Fig. 6 - Probable Error in Bottom Loss vs. Frequency

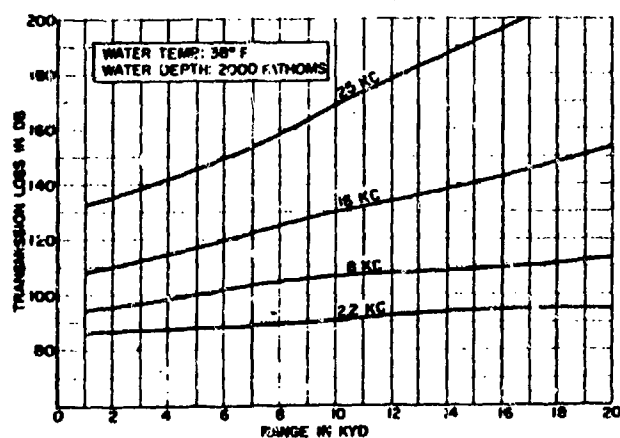


Fig. 7 - Transmission Loss vs. Range for Bottom-Reflected Transmission

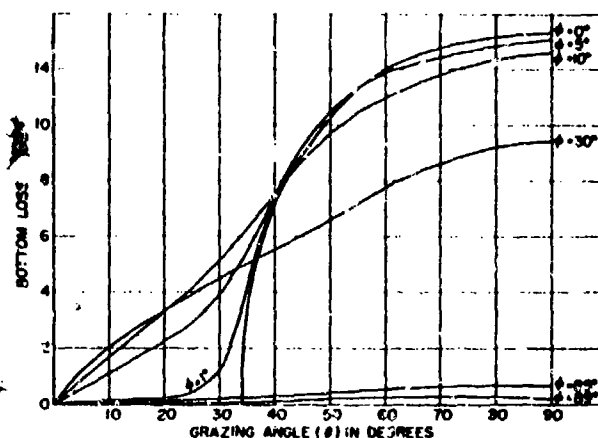


Fig. 8 - Rayleigh Theoretical Bottom Loss vs. Grazing Angle ( $\rho$ ,  $c$  constant)

geneous, fluid medium (sea water) impinging on the surface of separation for a second infinite, homogeneous, fluid medium (the bottom). In the second case consider that the bottom is composed of an absorbing fluid overlying a hard, perfectly reflecting surface.

In the first case the Rayleigh formula for the energy reflection coefficient is:

$$R_B = \left| \frac{\zeta \sin \theta_g - \sqrt{1 - \cos^2 \theta_g (c_2/c_1)^2}}{\zeta \sin \theta_g + \sqrt{1 - \cos^2 \theta_g (c_2/c_1)^2}} \right|^2 \quad (1)$$

where

$\theta_g$  = grazing angle with bottom and  
 $\zeta = \rho_2 c_2 / \rho_1 c_1$ .

Here,  $c_2$  is complex and  $c_1$  is the speed of sound in sea water; then

$$c_2 = |c_2| (\cos \phi - i \sin \phi) = |c_2| e^{-i\phi}.$$

In Fig. 8, the reflection coefficient is plotted against the grazing angle for a number of phase angles,  $\phi$ , for the sound speed in the bottom. For the purposes of calculation, typical density ratios of  $\rho_2/\rho_1 = 1.3$  and for  $|\zeta| = 1.555$  were used. The main features of these curves are that (1) when the phase angle  $\phi$  is close to zero, there is a critical angle of about  $34^\circ$  for which there is total reflection for all grazing angles up to this value; (2) for grazing angles of  $5^\circ$  and  $10^\circ$  the reflection coefficient decreases continuously in the "region of

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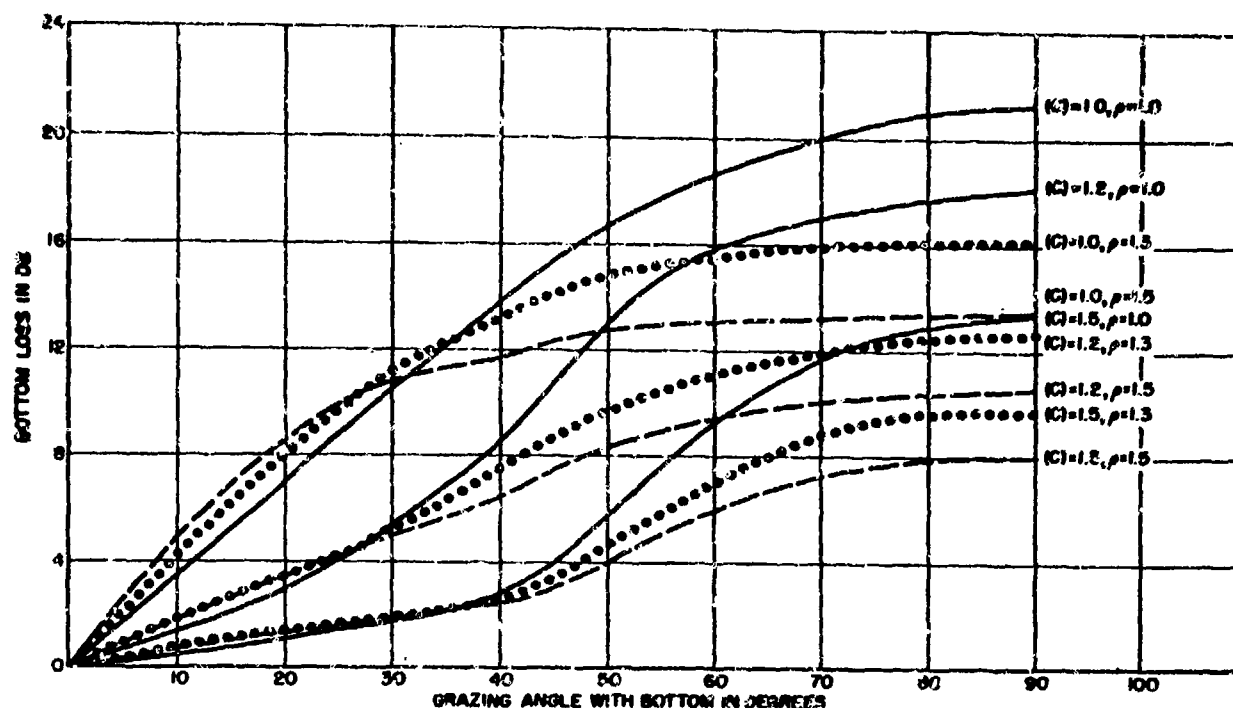


Fig. 9 - Rayleigh Theoretical Bottom Loss vs. Grazing Angle (Phase Angle constant)

total reflection," i.e., there is no region of total reflection; and (3) as the phase angle increases from 30° to 90° the reflection coefficient improves steadily and the grazing angle dependence for each phase angle is continuous.

In Fig. 9, the phase angle is kept fixed at 10°, and the variation of reflection coefficient with sound speed ratio is computed for different density ratios. It may be seen that the better matched the two media are, the poorer is the reflection coefficient. The purpose of computing these curves is to find the actual magnitudes involved. It may be seen that the previous model does not show the main features of the observed reflection coefficient data except at very low frequencies.

At the higher frequencies, there is an increase in reflection coefficient at greater grazing angles that needs explaining. The shape of the reflection coefficient curves at higher frequencies may be accounted for in various ways. For example, it may arise from a predominant specular reflection at small grazing angles and a predominant scattering effect at high grazing angles. Another possibility is that in the deep ocean a sound absorbing sediment layer overlies a harder, perfectly re-

flecting sediment which will accentuate the behavior above a certain frequency. There is some reason to believe that this last model has some physical justification from studies of deep sea sediments.<sup>4</sup>

If a plane wave is incident on a bottom composed of a sound absorbing layer of thickness,  $D$ , overlying a hard, infinite medium, then it can be shown that the amplitude reflection coefficient is given by:

$$R_A =$$

$$\frac{\zeta \sin \theta_1 - (\sqrt{1 - (c_2/c_1)^2} \cos^2 \theta_1) (i \tan \alpha D) \sin \theta_2/c_2}{\zeta \sin \theta_1 + (\sqrt{1 - (c_2/c_1)^2} \cos^2 \theta_1) (i \tan \alpha D) \sin \theta_2/c_2} \quad (2)$$

where

$$\sin \theta_2 = \sqrt{1 - (c_2/c_1)^2} \cos^2 \theta_1.$$

<sup>4</sup> See Table 121, p. 1039, of *The Ocean* by H. U. Sverdrup, M. V. Johnson, and E. H. Fleming, Prentice-Hall, Inc., 1942.

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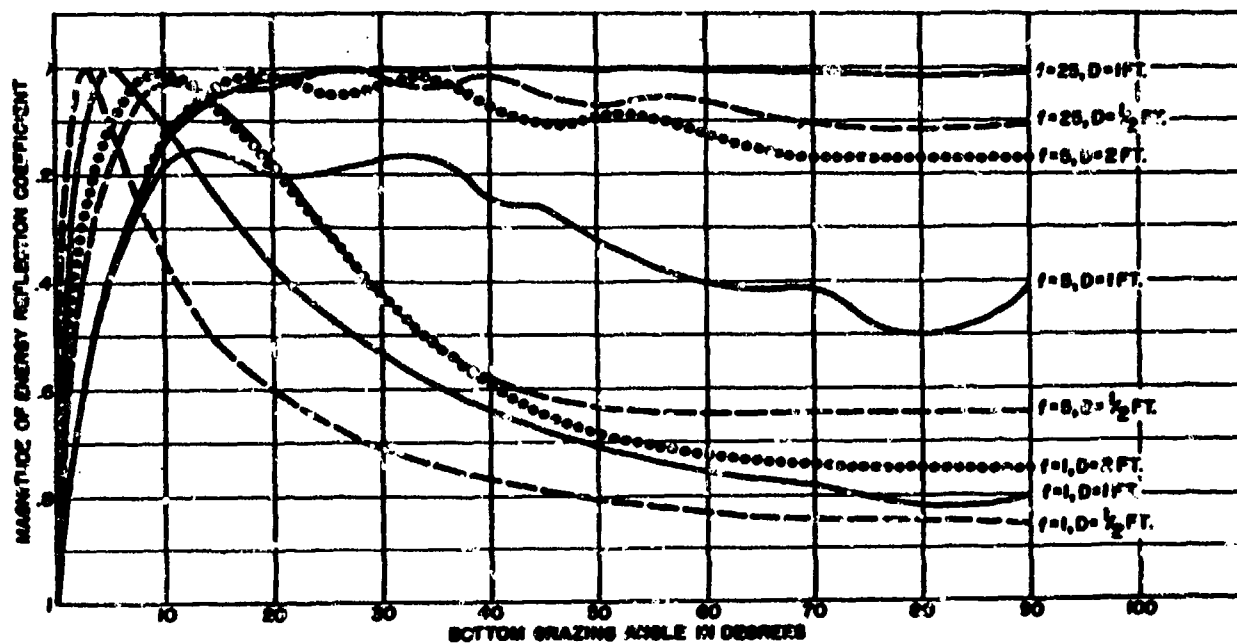


Fig. 10 - Magnitude of Energy Reflection Coefficient vs. Bottom Grazing Angle

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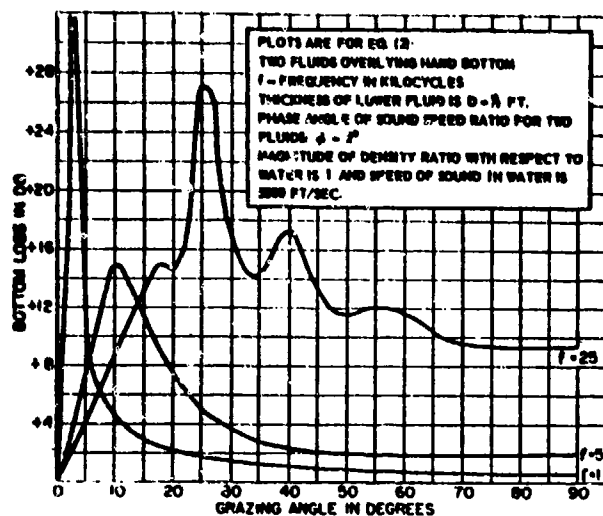


Fig. 11A - Second Fluid Thickness =  $\frac{1}{2}$  foot

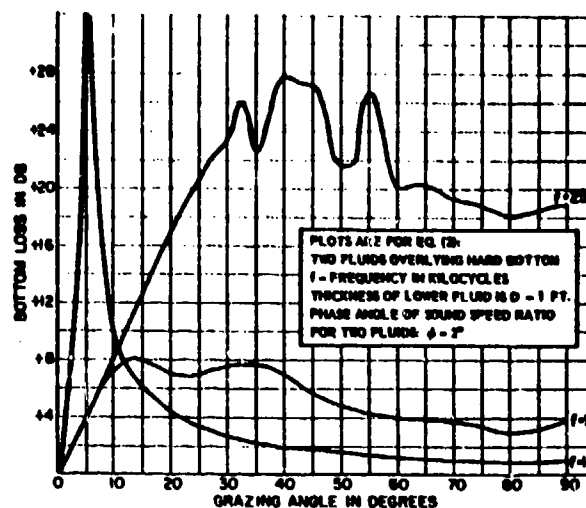


Fig. 11B - Second Fluid Thickness = 1 foot

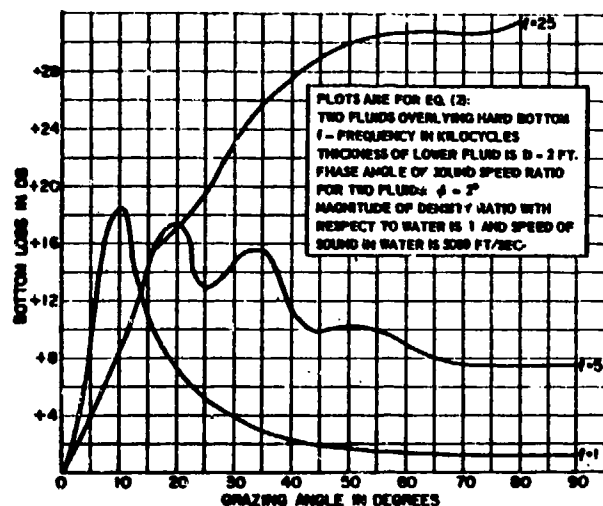


Fig. 11C - Second Fluid Thickness = 2 feet

Fig. 11 - Computed Bottom Loss vs. Bottom Grazing Angle

For the purposes of computation,

$$\phi = 2^\circ,$$

$$C_1 = 5000 \text{ ft/sec},$$

$$C_2 = C_1 - iC_i = \sqrt{C_1^2 + C_i^2} e^{-i\phi}, \text{ and}$$

$$|C_2| = C_1 / \cos \phi.$$

In Fig. 10, the square of the absolute value of the reflection coefficient is plotted against grazing angle for various products of  $f$  and  $D$ . These are replotted in Figs. 11A, 11B, and 11C in terms of reflection loss in db. It may be seen that the shape of the curves and order of magnitude of reflection loss at the higher frequencies are suggestive of the average measured behavior. At the lower frequencies the simple, two-fluid model computations in Fig. 8 look like the measured curves in Fig. 5. The computations are merely meant to be suggestive of possibilities rather than to be applicable to the data.

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## STUDY E

### LATERAL RANGE CURVES FOR HULL-MOUNTED ECHO-RANGING SONARS<sup>1</sup>

by

M. Schulkin and R. A. Spong

#### INTRODUCTION

Lateral range curves are included for hull-mounted, echo-ranging sonars at frequencies of 25 and 10 kc under various environmental conditions.<sup>2</sup> A discussion of sonar figure of merit is presented, together with typical values for the various systems used by the Fleet. The use of such lateral range curves in search and screening operations is considered briefly.

#### LATERAL RANGE CURVES

A number of sets of lateral range curves (see Figs. 1 and 2) have been prepared for use with hull-mounted, echo-ranging sonars at different frequencies. Curves at frequencies of 25 and 10 kc are included in this study. The curves apply to deep water off the Continental Shelf.

A lateral range curve is a plot of the probability of detecting a submarine which is moving in a parallel track with respect to a searching vessel, against the track separation. Such curves offer the tactician a basis for establishing reliable tactics with respect to the sonar situation. A screen commander may choose between alternative tactics by determining the level of probability of detection associated with a given ship positioning. The curves may also be used in working out force requirements in convoy routing.

Each set of lateral range curves has been prepared for a specified frequency and is to be used for equipment at that frequency. In using these curves, that set of lateral range curves is selected which applies most closely to the existing envi-

ronmental conditions of temperature and isothermal layer depth. The curves for  $L = 0$  are for negative temperature gradients starting at the surface.

There are two columns of three curves on each page for the indicated isothermal depth,  $L$ , in feet, water temperature, degrees F., and sea state 0-2. The dashed tails which are present on some of the curves apply to the effect of sea states greater than 3 on sonar system performance. Curves with no dashed sections can be used for all sea state conditions. One column of the page applies to a submarine at periscope depth, 50 feet; the other column is for a submarine within 500 feet of the surface, its best depth for avoiding detection. The submarine depth is indicated by the symbol  $Z$ , and its value is listed next to the layer depth value. The curves are labeled with figures of merit in db. A change in range scale was found to be convenient to use for the deeper isothermal layers.

#### FIGURE OF MERIT OF ECHO-RANGING SONARS

If the figures of merit of hull-mounted, echo-ranging sonars have been measured as a function of range for specified operational conditions, then a complete lateral range curve may be found from the curves of this report.

The figure of merit of an echo-ranging system is the permissible loss of the system under a given set of conditions and is the difference between the power source level, in db//1  $\mu$ b at 1 yd, and the operational minimum detectable echo level, in db//1  $\mu$ b. In order to determine its sonar figure of merit, a ship performs operational maneuvers at sea while an artificial echo is inserted at an arbitrary range and bearing. While the sonarman is using standard search procedure in locating the target, the level of the artificial echo is increased at a rate corresponding to the closing of range between the target and the searching vessel. The back-

<sup>1</sup> This report was issued originally as USL Technical Memorandum No. 1110-018-54, 1 July 1954 (CONFIDENTIAL).

<sup>2</sup> The original memorandum included lateral range curves at 20 and 14 kc.

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ground of noise and reverberation is the actual interference against which the sonarman would have to work in locating a real target.

Typical measured values of the figures of merit of various sonars are shown in Fig. 3. Here the average figure of merit of the Q1B3 sonar is plotted as a function of range. The data were obtained on 27 destroyers in 1951. In addition, figure-of-merit plots of other sonars on individually specified ships are given. It was found in this investigation that the figure of merit did not change with higher sea states through sea state 5. However, quenching of the sonar and rolling of the ship reduced the probability that a signal would insonify the target and that the resulting echo would be detected. It was also found that sonar operators have a psychological tendency to work with the gain tuned down too low, affording a dark background beyond the range of reverberation effects. Considerable improvements in detection range can be achieved by turning the gain up to the point where noise speckles just begin to appear at the greater ranges on the scope.

#### USE OF LATERAL RANGE CURVES

There is a well-developed theory for the use of lateral range curves for search and screening operations. The range measure usually considered in this connection is the sweep width. This is the area under the probability curve or the effective width

of the rectangular area swept by the antisubmarine vessel in searching operations.

The lateral range curve is a very flexible presentation of the range performance of a sonar system. The spacing between ships of a screen may correspond to a high level of probability of detection when a tight screen is required, or to a lower level of probability of detection when a loose screen is desired.

Lateral range curves may be used to plan force requirements in convoy or hunter-killer group operations. The relative performance of diverse sonars according to frequency, power, and detection sensitivity may be taken into account in these plans.

The best search speed for area coverage may be determined by plotting the product of the sweep width or a range corresponding to a given level of detection by the ship speed. Since the figure of merit varies with ship speed, it will be found that the product may have a maximum value at a given speed. This will be the best search speed for the individual ship. The best search speed may vary from ship to ship, and one may decide to use the best average speed for all ships or employ some tactic which takes advantage of the optimum search speed for individual ships.

The curves may also be used to determine the optimum keying interval. If environmental or operational conditions are such that poor ranges are achieved, then a more rapid search out to a shorter range is advisable.



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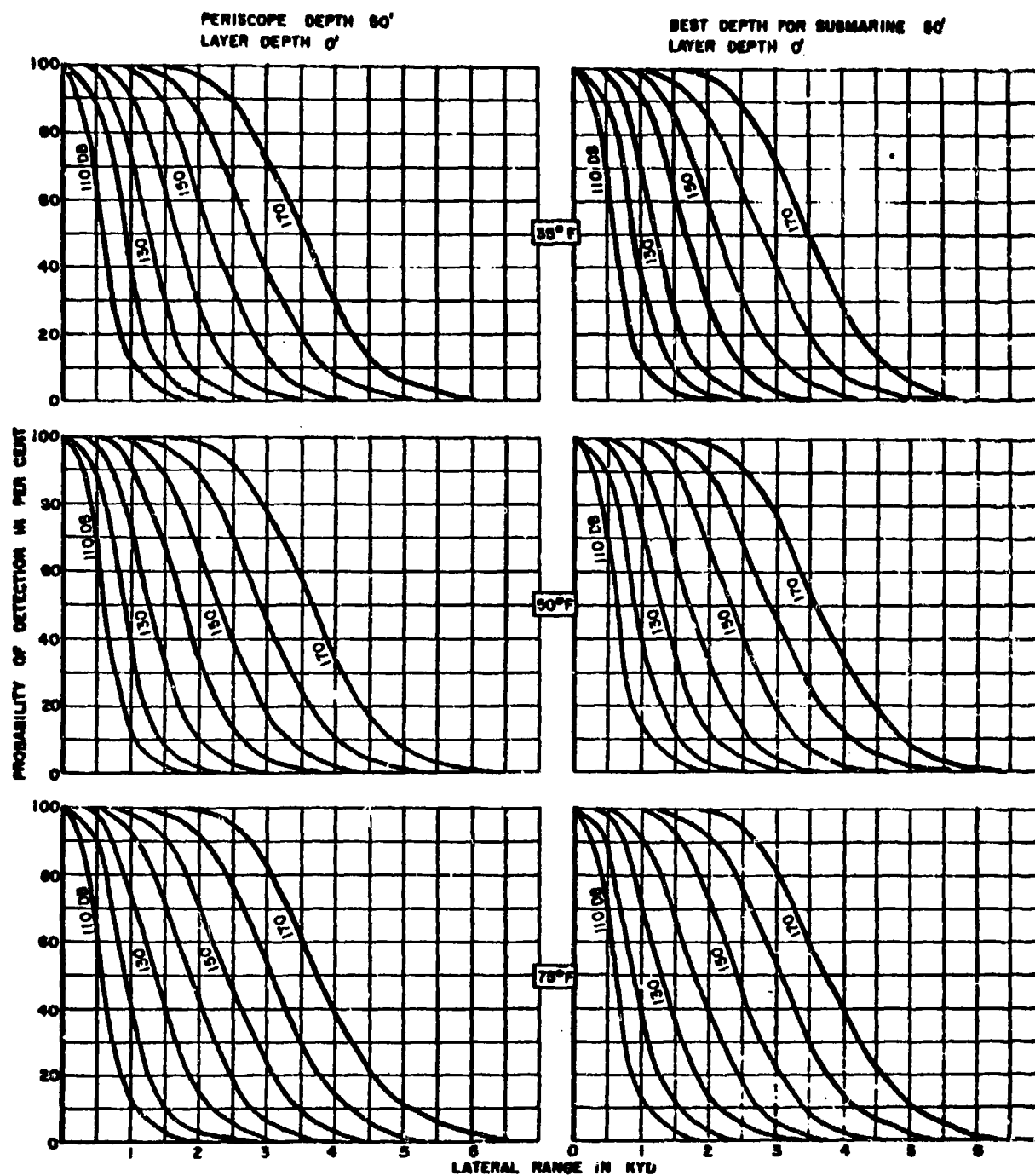


Fig. 1A - Lateral Range Curves for 10-kc Hull-Mounted Echo-Ranging Sensor

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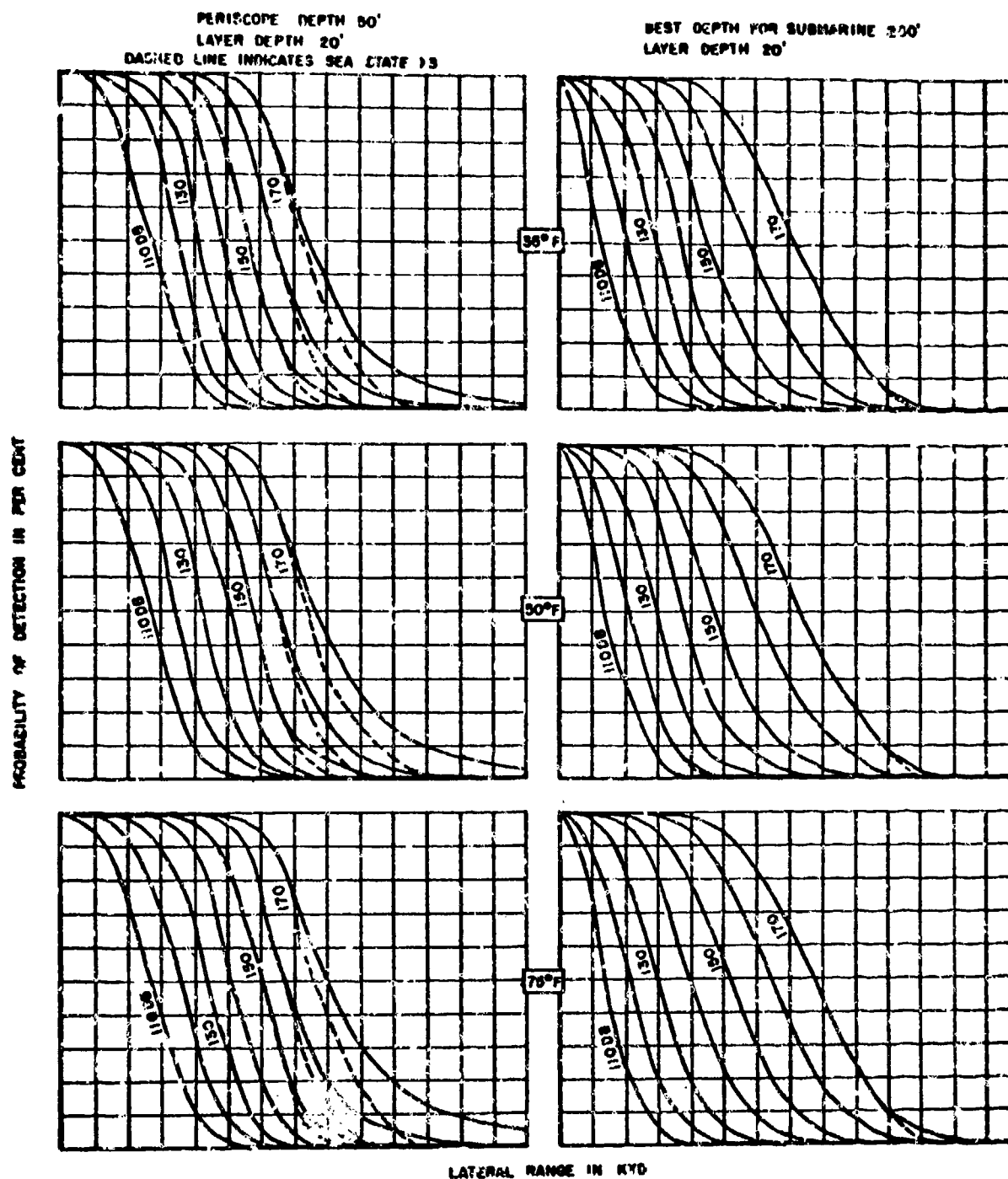


Fig. 1B - Lateral Range Curves for 10-kc Hull-Mounted Echo-Ranging Sonar

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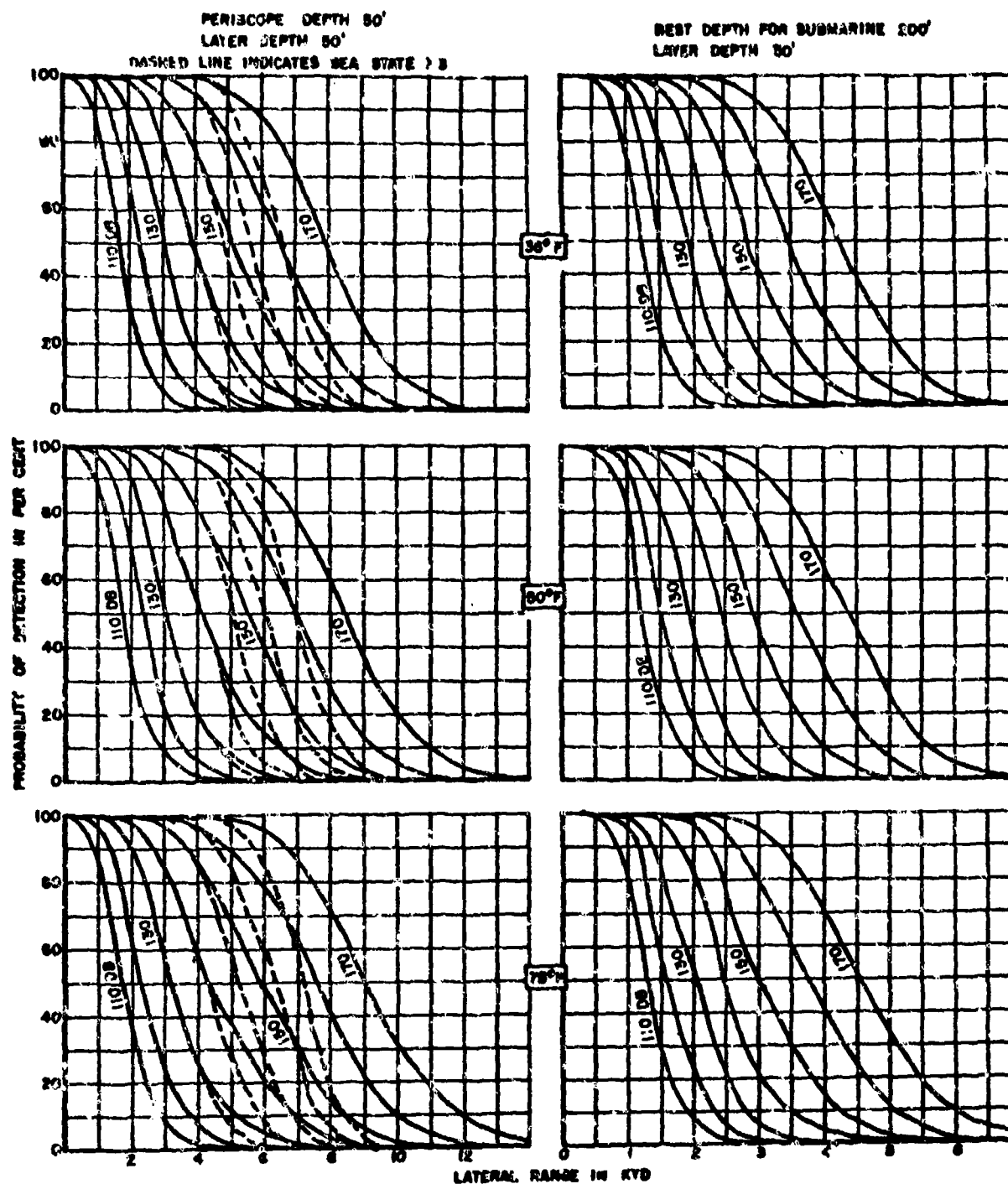


Fig. 1C - Lateral Range Curves for 10-kc Hull-Mounted Echo-Ranging Sonar

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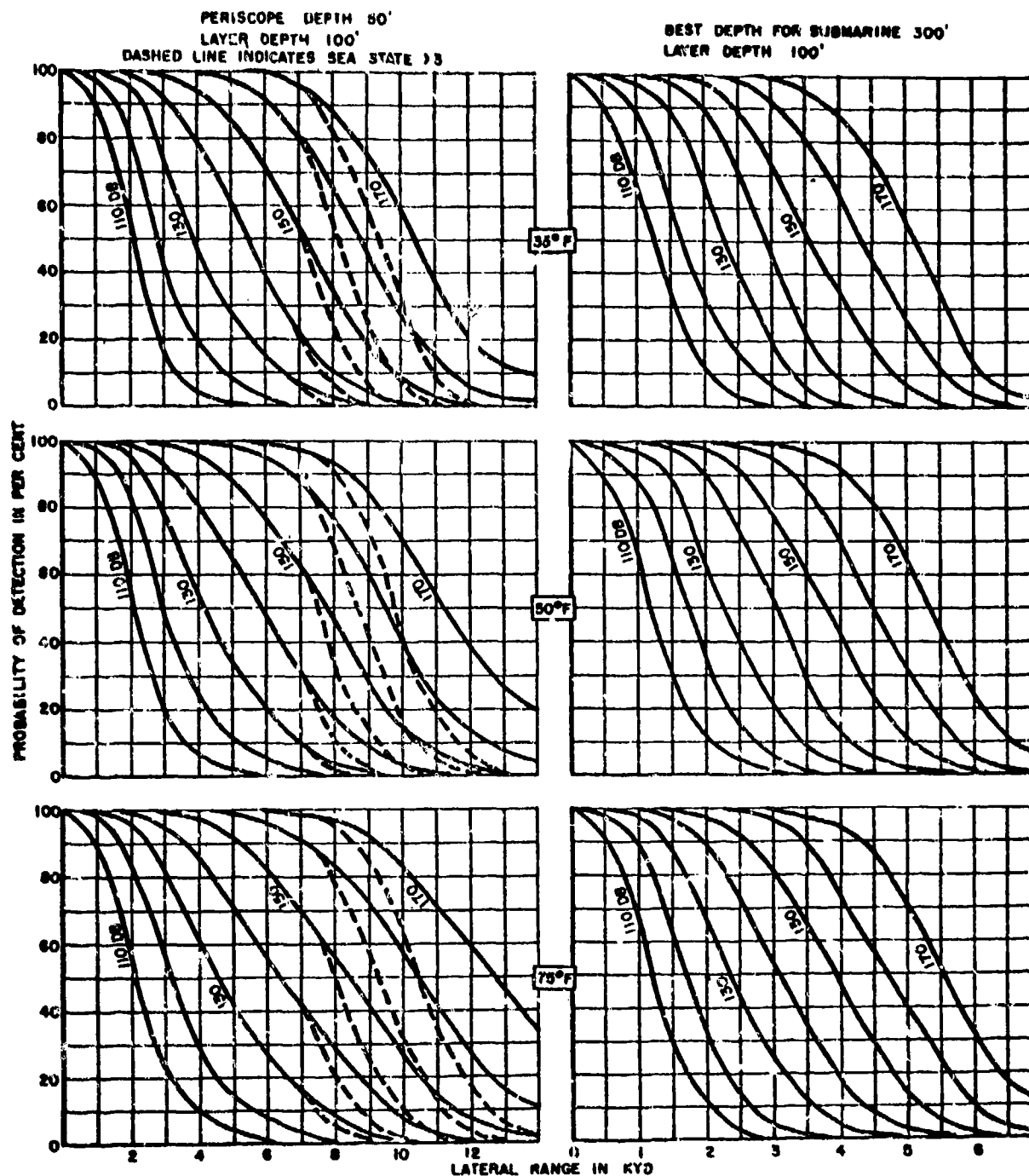


Fig. 1D - Lateral Range Curves for 10-kc Hull-Mounted Echo-Ranging Sonar

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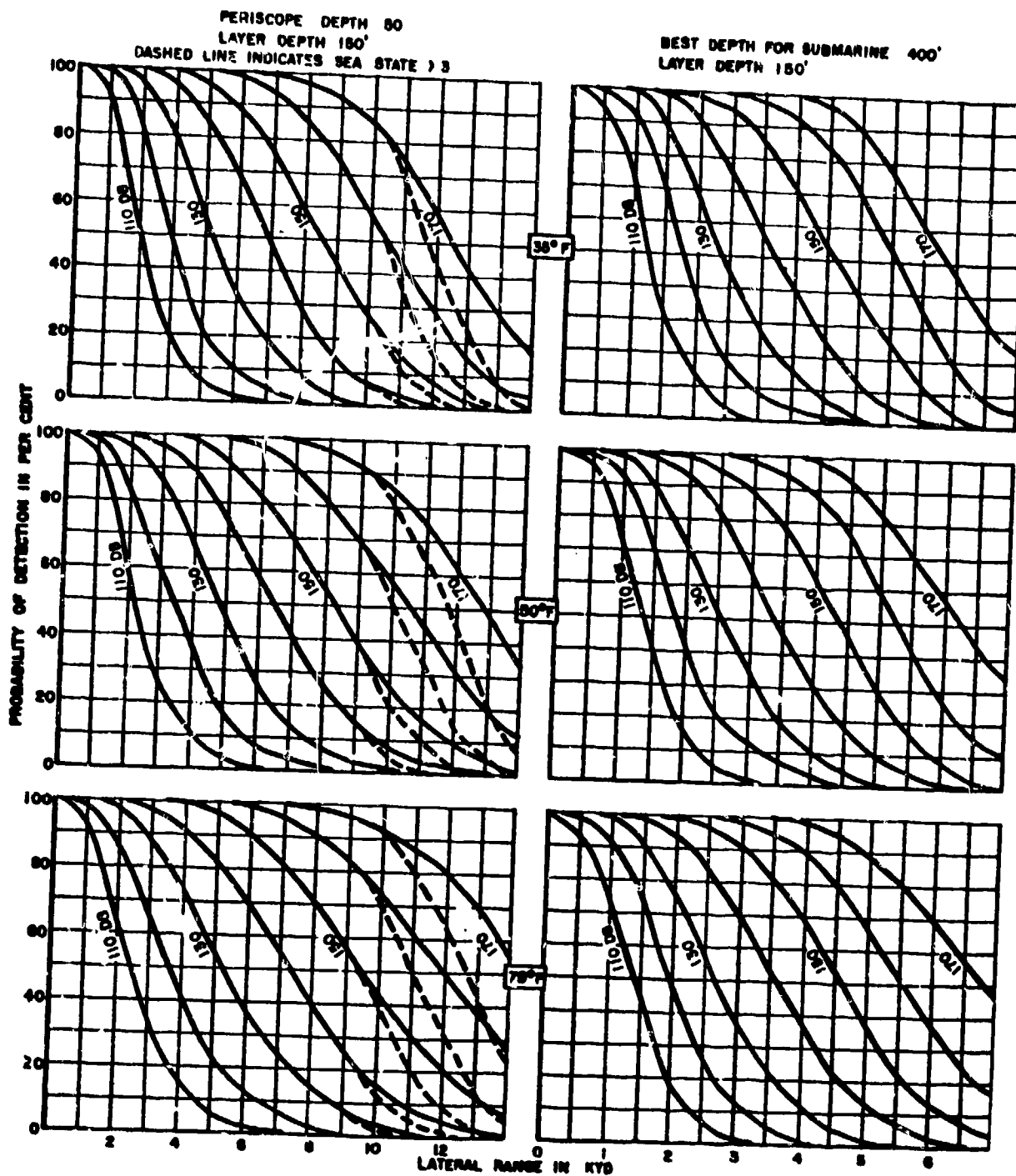


Fig. 1E - Lateral Range Curves for 10-kc Hull-Mounted Echo-Ranging Sonar

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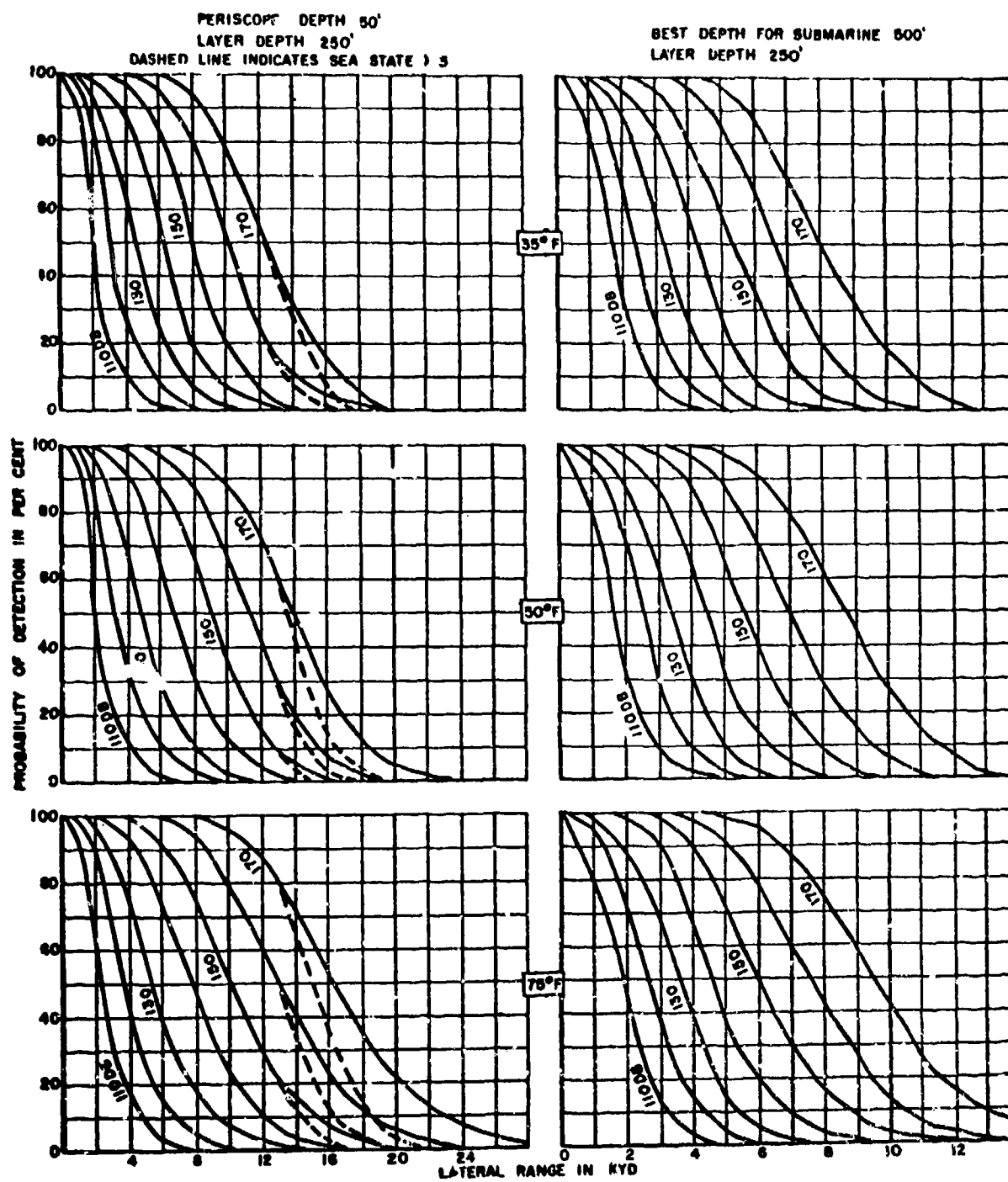


Fig. 1F - Lateral Range Curves for 10-kc Hull-Mounted Echo-Ranging Sonar

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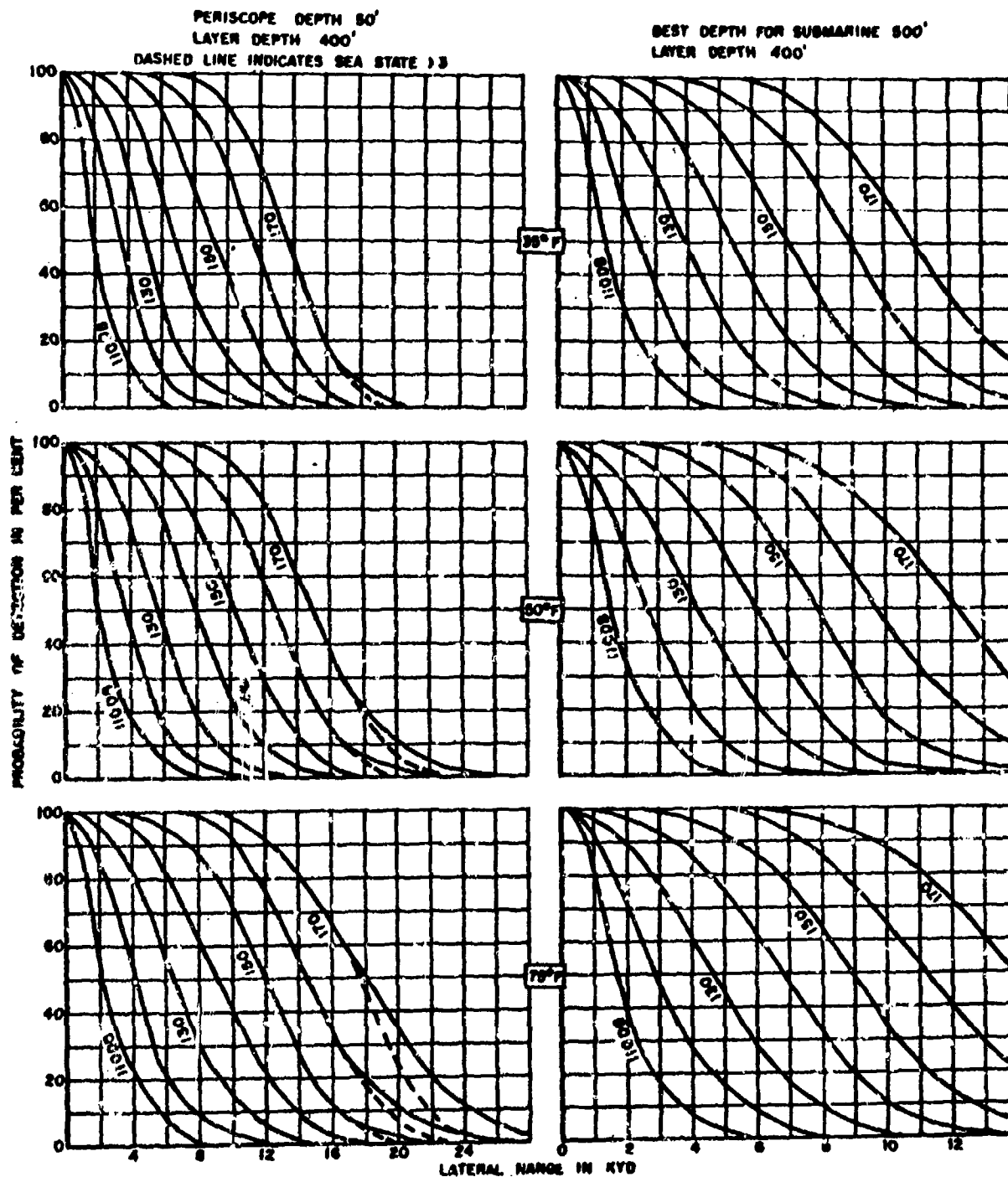


Fig. 1G - Lateral Range Curves for 10-kc Full-Mounted Echo-Ranging Sonar

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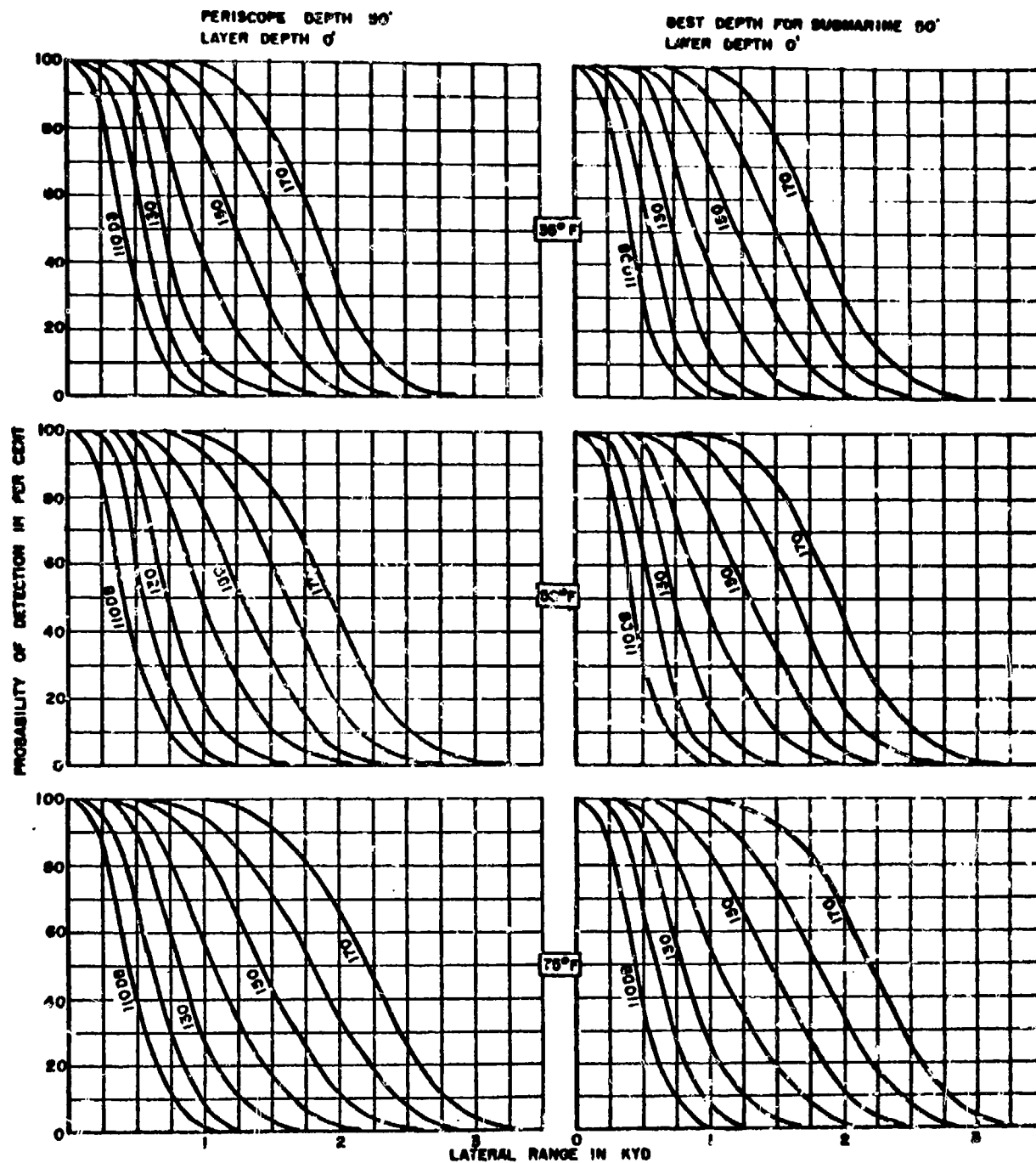


Fig. 2A - Lateral Range Curves for 25-ke Hull-Mounted Echo-Ranging Sonar

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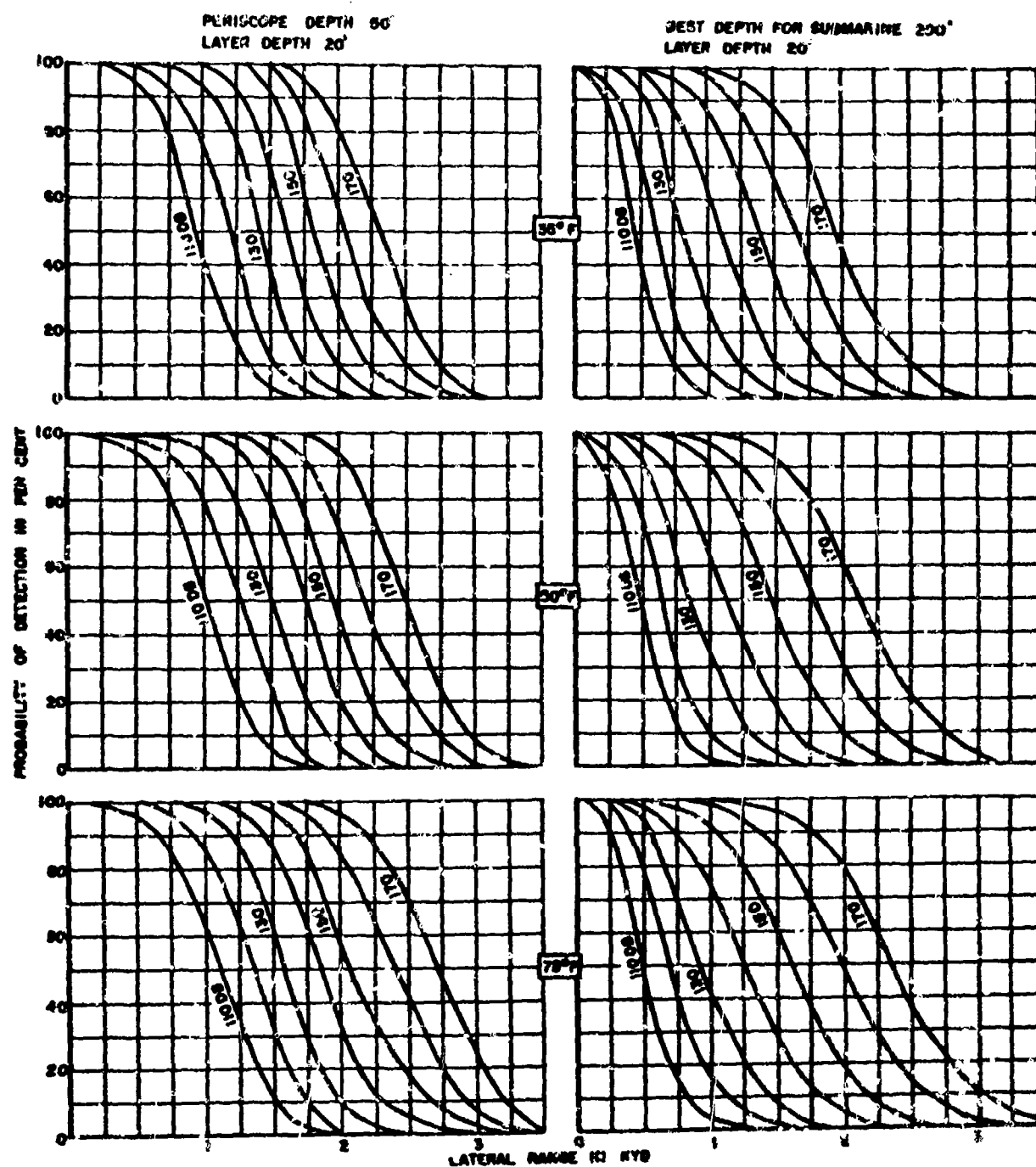


Fig. 2B - Lateral Range Curves for 25-L Hull-Mounted Echo-Rangeing Sonar

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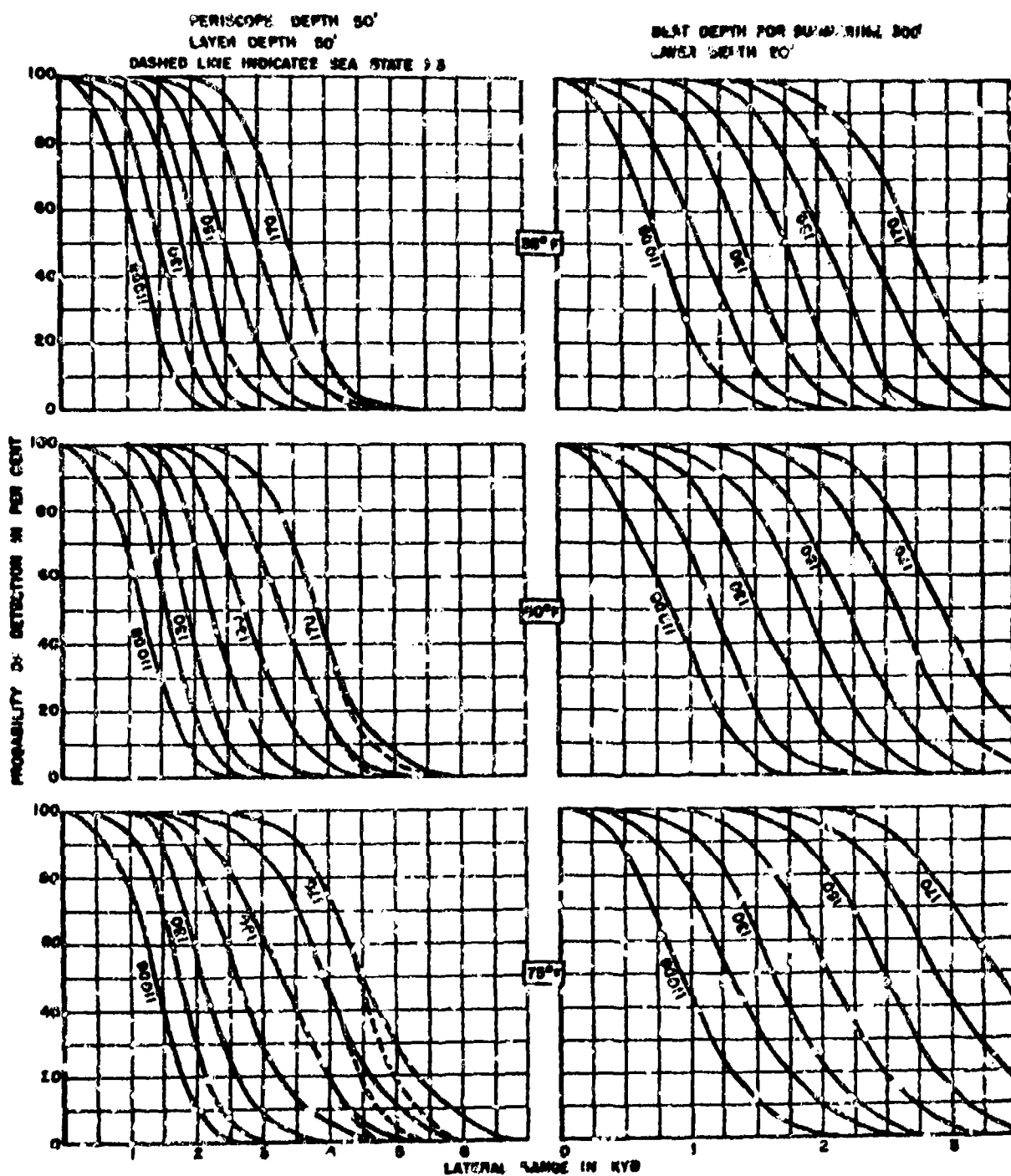


Fig. 2L - Lateral Range Curves for 25-kc Hull-Mounted Echo-Ranging Sonar

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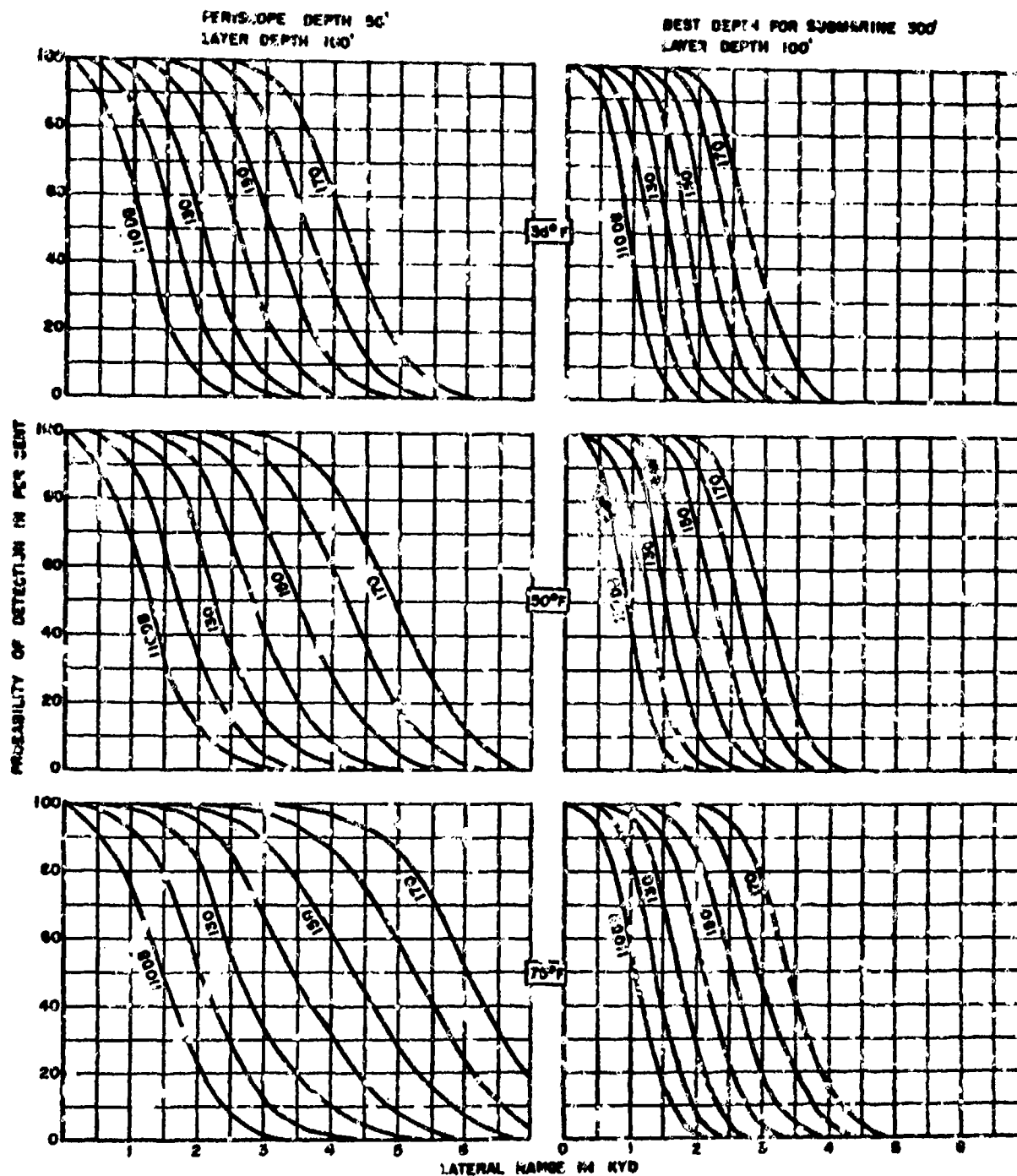


Fig. 2D - Lateral Range Curves for 25-kc Hull-Mounted Echo-Rangeing Sonar

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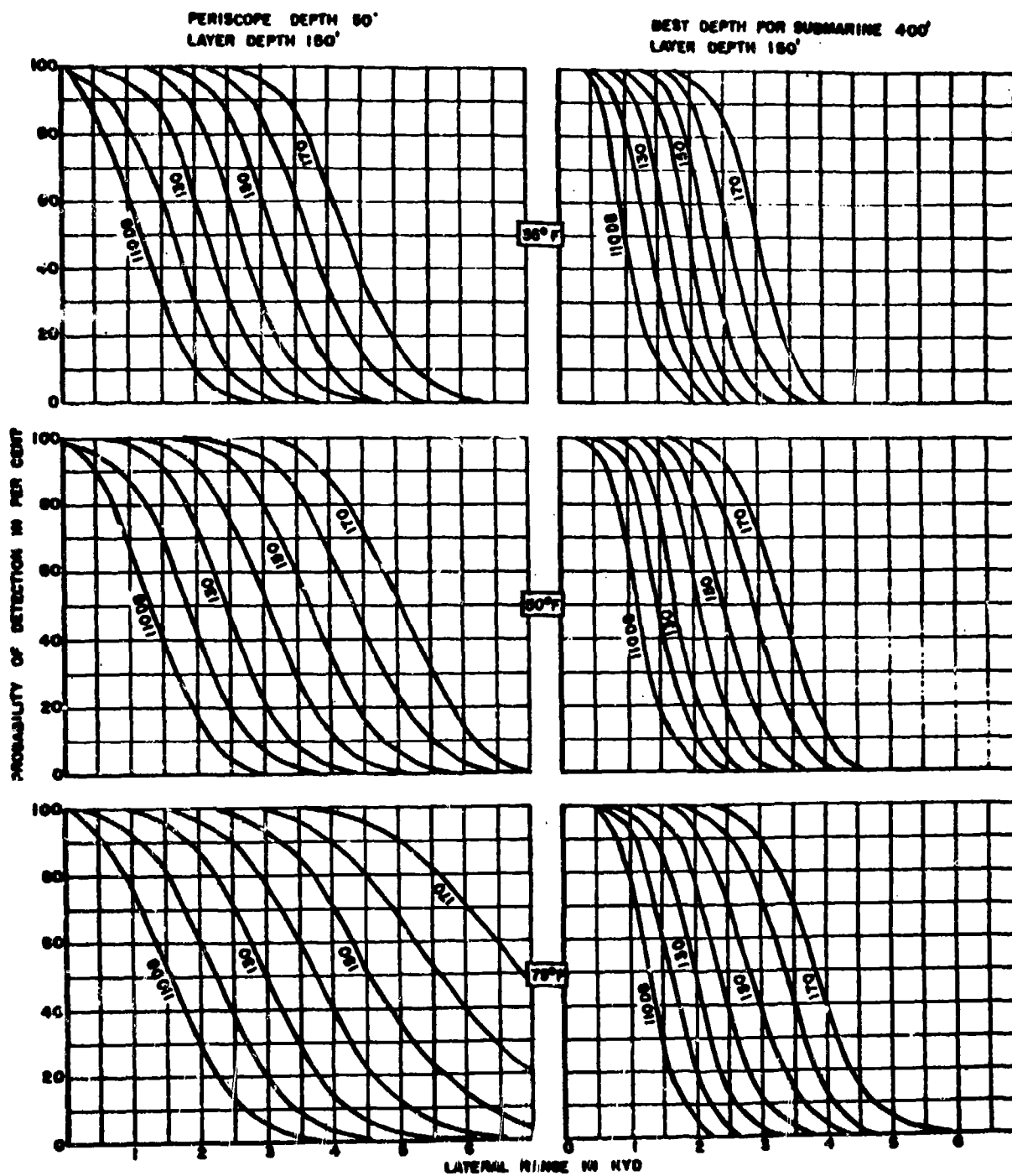


Fig. 2E - Lateral Range Curves for 25-kc Hull-Mounted Echo-Ranging Sonar

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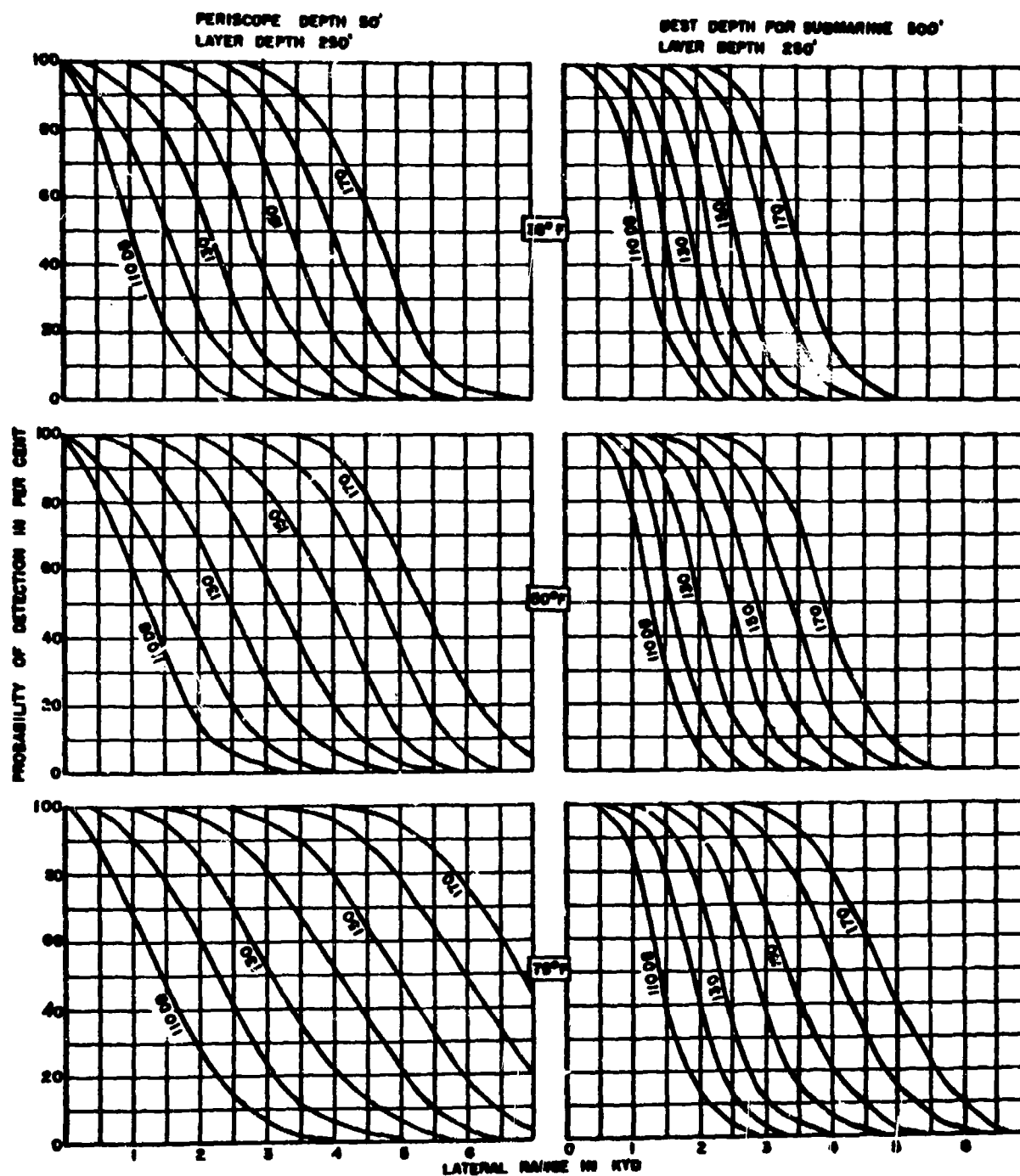


Fig. 2F - Lateral Range Curves for 25-kc Hull-Mounted Echo-Ranging Sonar

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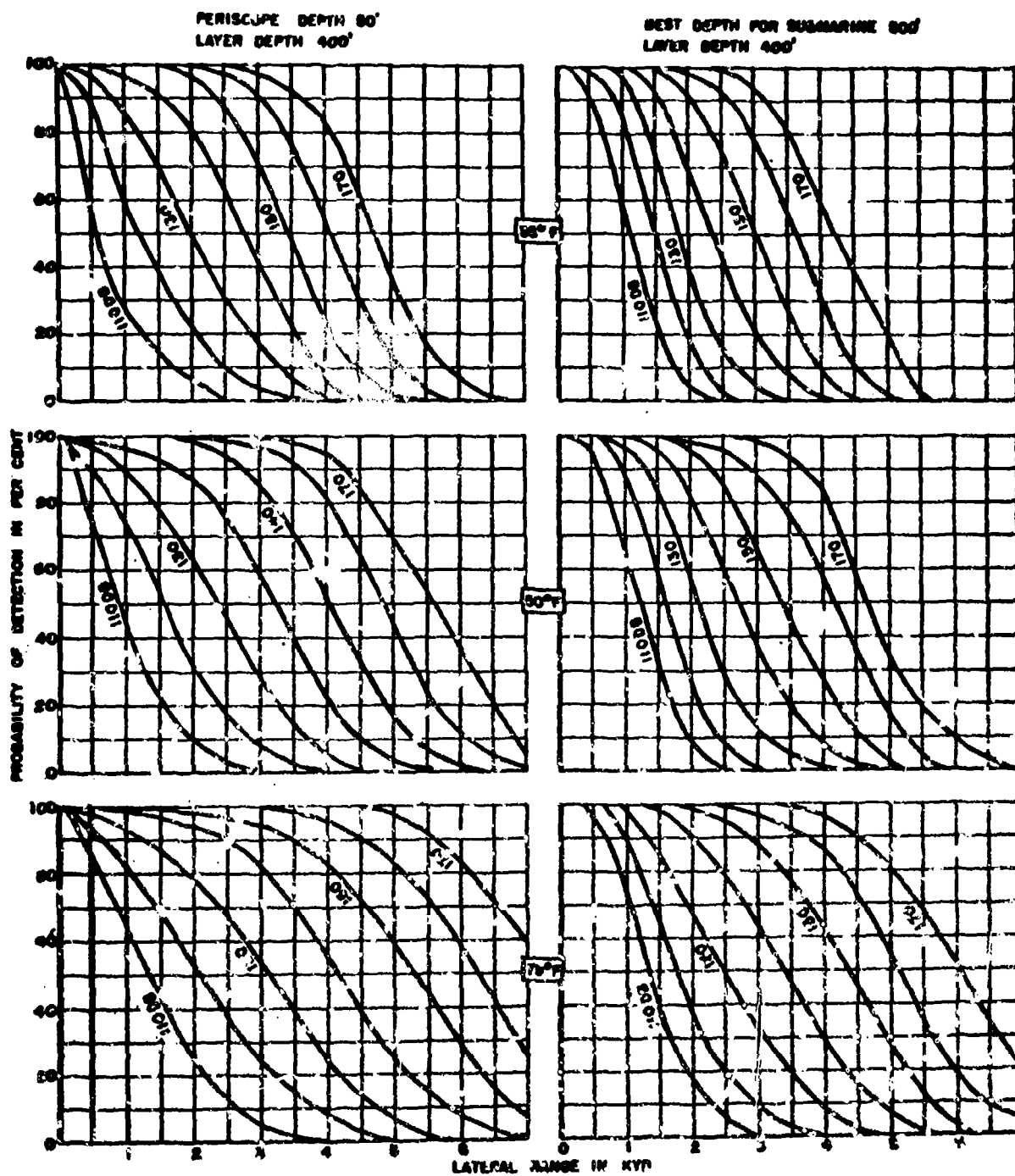


Fig. 2G - Lateral Range Curves for 25-kc Hull-Mounted Echo-Ranging Sonar

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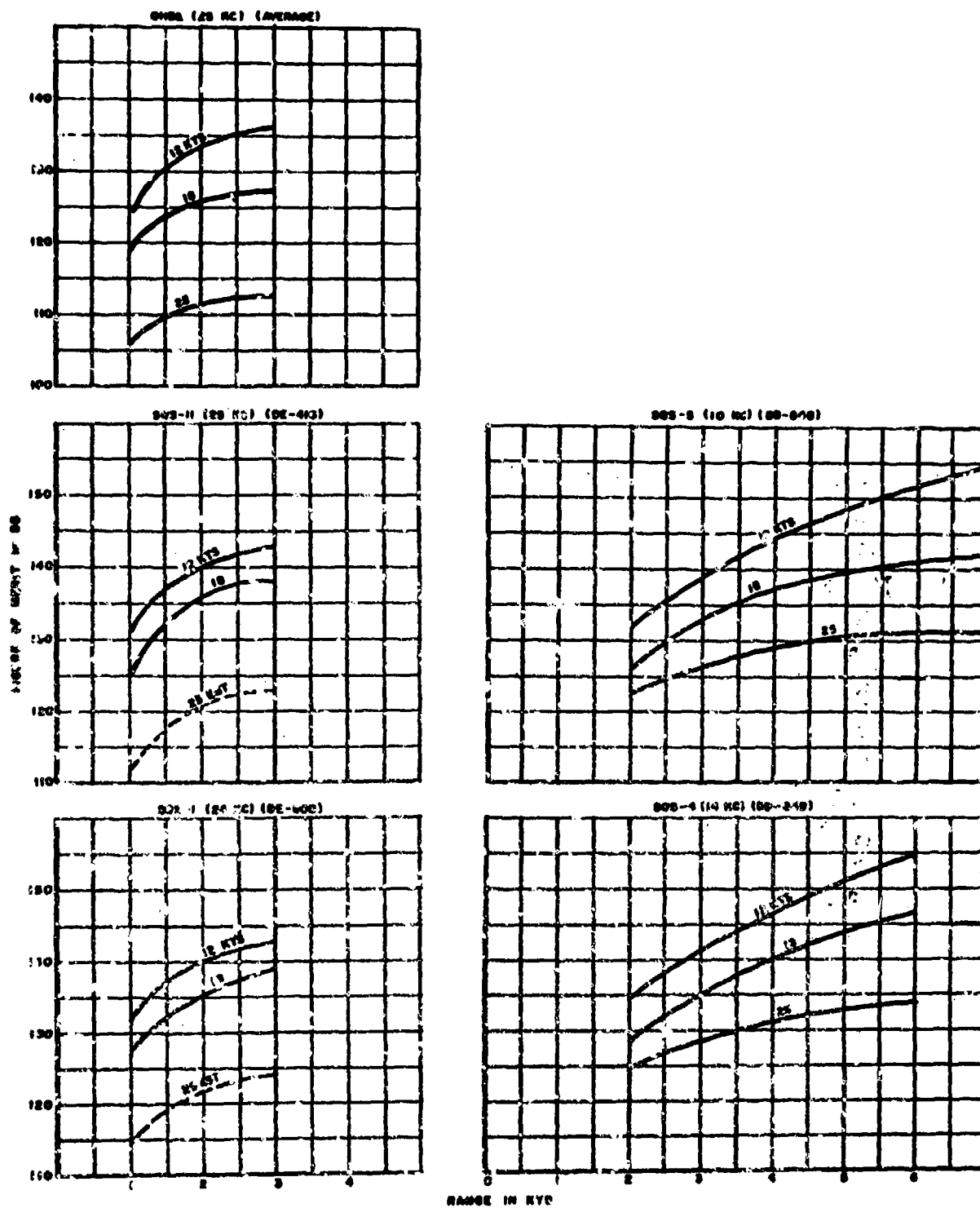


Fig. 3 - Operational Figure of Merit of Sonar Systems (Deep Water)

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## STUDY F

## COMPARATIVE PERFORMANCE OF ECHO-RANGING SONARS

by

M. Schulkin, R. E. Ballwe, and R. A. Spong

This paper presents evidence which shows that reliable range predictions can be made by using figure-of-merit measurements, available target-strength information, and Project AMOS propagation data. A comparison of expected range performance for hull-mounted and variable-depth sonars under uniform conditions is included. Lateral range curves based on the USL range prediction methods have been used successfully in convoy-escort screen design.

For several years the Underwater Sound Laboratory has been obtaining equipment figure-of-merit measurements and associated detection ranges on different types of echo-ranging sonars.<sup>1</sup> In recent antisubmarine warfare development exercises (AS DevEx-I) additional data of this type were obtained under identical environmental conditions. As a result of these two spheres of experience, the Laboratory is in a position to prepare lateral range curves and to compute sweep widths and expected ranges for system design and tactical applications.

This paper presents evidence which shows that reliable range predictions can be made by using figure-of-merit measurements, available target-strength information, and Project AMOS propagation data. Also included is a comparison of expected range performance for hull-mounted and variable-depth sonars under uniform conditions. The three factors used in predicting sonar range performance, namely, equipment figure of merit,

target strength, and propagation loss, will now be discussed in that order.

The figure of merit of an echo-ranging system is the permissible loss of the system under a given set of conditions in obtaining detection and is the difference between the power source level, in db/1  $\mu$ b at 1 yd, and the operational minimum detectable echo level, in db/1  $\mu$ b. In order to determine its sonar figure of merit, a ship performs operational maneuvers at sea while an artificial echo is inserted at an arbitrary range and bearing. While the sonarman is using standard search procedure in locating the target, the level of the artificial echo is increased at a rate corresponding to the closing of range between the target and the searching vessel. The background of noise and reverberation is the actual interference against which the sonarman would have to work in locating a real target.

Table 1

FIGURE OF MERIT OF  
QHBA ECHO-RANGING SONARS (25.5 kc)  
(Noise-Limited Conditions; Ship Speed 15 knots)

QHBA System	Source Level at 1 yd (db/1 $\mu$ b)	Minimum Detectable Echo Level (db/1 $\mu$ b)	Figure of Merit (db)
Average (1951)	107	-24 $\pm$ 8	131 $\pm$ 8
GREENWOOD	106	-15 $\pm$ 3	121 $\pm$ 3
MALOY	111	-31 $\pm$ 7	142 $\pm$ 7
Tri-Beam, MALOY	125	-37 $\pm$ 6	162 $\pm$ 6

Table 1 presents the figure of merit of QHBA echo-ranging sonars at 25.5 kc.<sup>2</sup> The sonars are noise-limited, and the ship speed is 15 knots. The last column lists the figure of merit, which is the

<sup>1</sup> This program has been documented in several USL reports. See M. Schulkin, *History, Development, and Present Status of Project AMOS (Acoustic, Meteorological, and Oceanographic Survey)*, USL Report No. 132, 20 April 1951 (CONFIDENTIAL); H. W. Marsh, Jr., and M. Schulkin, *Report on the Status of Project AMOS (20 April - 31 December 1951)*, USL Report No. 147, 19 February 1952 (CONFIDENTIAL); M. Schulkin, F. S. White, Jr., and R. A. Spong, *QHBA Figure-of-Merit Tests*, USL Report No. 187, 3 April 1953 (CONFIDENTIAL); and H. W. Marsh, Jr., and M. Schulkin, *Report on the Status of Project AMOS (1 January - 31 December 1952)*, USL Report No. 188, 3 April 1953 (CONFIDENTIAL).

<sup>2</sup> The figure-of-merit measurements reported in this paper were obtained by the following USL staff members: F. S. White, Jr., W. B. Easley, Jr., R. F. Ballwe, and G. T. Adkins.



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Table 2

FIGURES OF MERIT OF ECHO-RANGING SONARS (Noise-Limited Conditions; Ship Speed, 15 knots)				
System	Frequency (kc)	Source Level at 1 yd (db/1 $\mu$ b)	Minimum Detectable Echo Level (db/1 $\mu$ b)	Figure of Merit (db)
SQS-11 (NAWMAN)	23.5	112	-20 $\pm$ 7	132 $\pm$ 7
(O'BRIEN)	23.5	112	-26 $\pm$ 6	138 $\pm$ 6
SQS-1 (WILKE)	24.0	122	-20 $\pm$ 2	142 $\pm$ 2
SQS-4 (WTEK)	14.0	117	-29 $\pm$ 4	146 $\pm$ 4
(KRAUS)	14.0	117	-31 $\pm$ 9	150 $\pm$ 9
SQS-5 (WTEK)	20.0	120	-27 $\pm$ 7	147 $\pm$ 7

difference between the source level and the minimum detectable echo level obtained under operational conditions. The average figure of merit based on 27 ships is shown on the first line. A poor system on the GREENWOOD and a good system on the MALOY are also shown. The GREENWOOD is 9 db poorer than the average in minimum detectable echo level, whereas the MALOY has a 5-db-better source level and a 7-db-better minimum detectable echo level. The Tri-Beam modification uses three beams on transmitting and speeds up the audio search rate, thus achieving a figure of merit which is 30 db better than the average.

In Table 2 the figure of merit of sonar systems at other frequencies is shown. The SQS-11 is essentially a higher-powered QHBA with a 5-db-better source level and, hence, a 5-db-better figure of merit. The SQS-1 has gained approximately 10 db through an improved source level. The SQS-4 at 14 kc achieves its high figure of merit through a higher source level and a somewhat lower operational minimum detectable echo level; the ships shown here are believed to be unusually quiet. The 10-kc SQS-5 also has a high source level. It should be repeated that since the figure of merit is the permissible loss in achieving detection, a low-frequency system will obtain a greater range than that of a higher-frequency system of the same figure of merit. This is so because the propagation loss in the water is greater the higher the frequency.

Target strength is the second factor used for range prediction computations. The curve shown in Fig. 1 is a composite of data obtained at approximately 25 kc through Project MYSTIC and by the Columbia University Division of War Research.

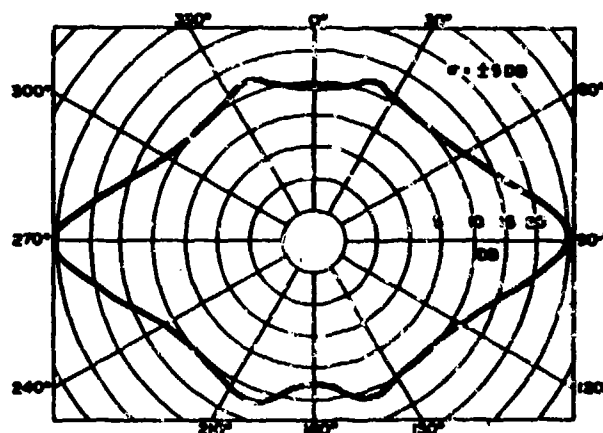


Fig. 1 - Submarine Target Strength, at 25 kc, vs. Submarine Target Aspect  
(Project MYSTIC and CUDWR Data)

The meager data reported at lower frequencies are in disagreement with the information in Fig. 1. The target strength is seen to be 25 db at beam aspect and 9 db at bow aspect. There is a standard deviation of  $\pm$  5 db at any particular aspect.

The third factor used in prediction of range is propagation loss.<sup>3</sup> Propagation losses are computed from the formulas and charts derived from a summary of the extensive Project AMOS measurements. Approximately a quarter of a million of these measurements were made. In the analysis of the measurements the following were found to be the

<sup>3</sup> A summary of the propagation-loss analysis is given by H. W. Marsh, Jr., and H. Schiffin in Study A of this report.

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significant factors: (1) depth of isothermal surface layer, (2) water temperature, (3) sea state (wind force), (4) depth of axis of depressed sound channel, (5) depth of ocean bottom, (6) range, (7) depth of source, (8) depth of receiver, and (9) acoustic frequency. Frequencies of from 2 to 25 kc were covered for various source and receiver depths and ranges.

A definite model of the ocean was used as a framework for the data analysis. According to this model, several modes or propagation paths determine the loss under any given set of circumstances.

In Fig. 2, underwater sound propagation zones associated with an isothermal layer and thermocline are sketched. On the left is the BT trace. Zone A is the region where energy from a source, say, at point 1 or 1', reaches any other point by a direct path. Energy reaches Zone B by way of at least one reflection from the sea surface or by diffraction from Zone A. Similarly, energy reaches Zone C through two or more surface reflections and diffraction from Zone B. In Zone A the energy initially follows a spherical spreading law. By the time the energy reaches Zone C, the spreading is cylindrical. Two other modes considered quantitatively in this model are propagation by way of internal channels and propagation by way of bottom reflection. The frequency-dependence and temperature effects on absorption have also been taken into account.

A sample set of one-way propagation-loss contours is shown in Fig. 3. They have been drawn for a frequency of 8 kc, a projector depth of 50 feet, and environmental conditions consisting of a 100-foot layer depth, a temperature of 50° F., and a 0-2 sea state. The axes are receiver depth in feet against range in kiloyards. At any range these curves will yield propagation loss as a function of depth under the specified conditions. Such basic charts also are available for other frequencies and projector depths. In order to obtain propagation loss at other layer depths, temperatures, and sea states, correction charts are used.

The ultimate test of any theory or prediction technique lies in a satisfactory comparison of measured and predicted performance. Comparisons of this type are given in Figs. 4, 5, and 6. In Fig. 4, each point represents the median of a group of homogeneous data with respect to environmental conditions and target depth. Each group was obtained from a series of lateral range runs or paral-



Fig. 2 - Underwater Sound Propagation Zones Associated with Isothermal Layer and Thermocline

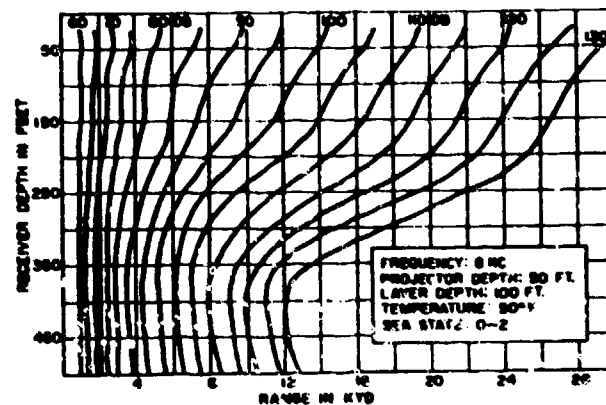


Fig. 3 - Propagation-Loss Contours (AMOS) in db

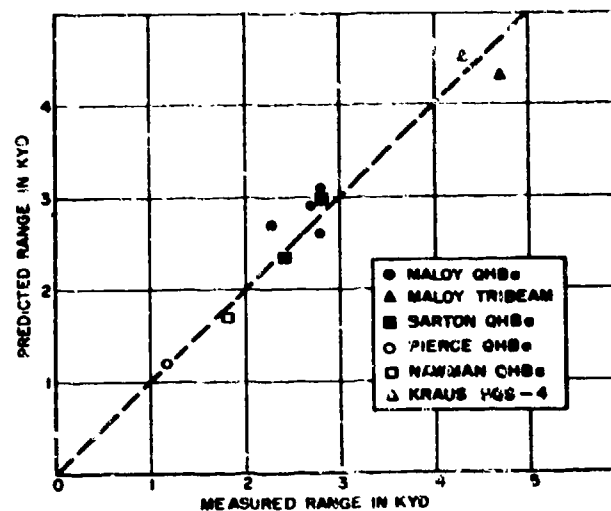


Fig. 4 - Comparison of Measured and Predicted Ranges (Points Represent Medians of Homogeneous Data Groups)

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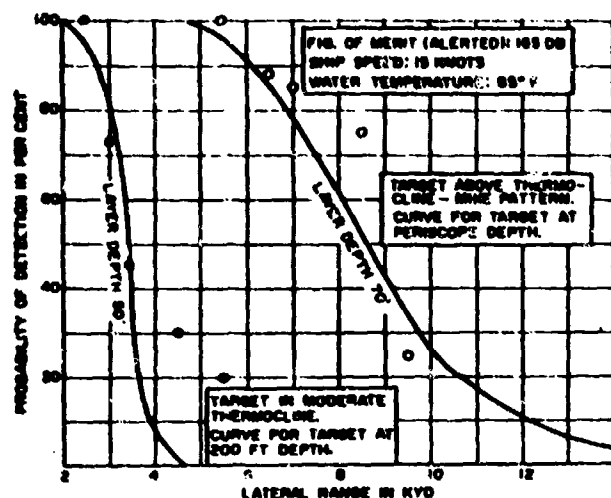


Fig. 5 - OpDevFor Evaluation Data (1953) for SQS-4 Sonar, together with USL Lateral Range Curves

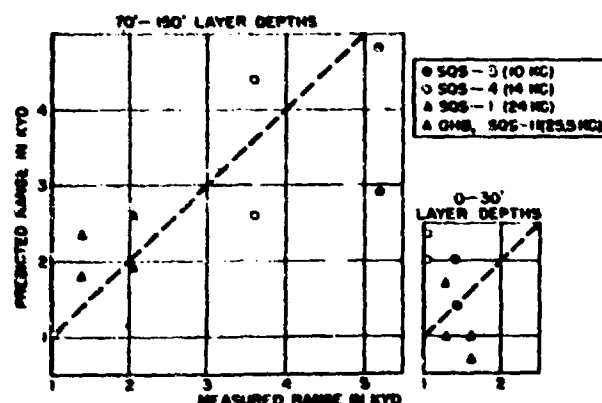


Fig. 6 - Comparison of Measured and Predicted Ranges (AsDevEx-1) (Points Represent Medians of Homogeneous Data Groups)

lateral sweeps with the destroyer moving at about 15 knots. Runs were started at different lateral ranges, and detections were made at different actual ranges and target aspects. Although most of the data plotted are for 25.5-kc systems, there was a large spread in figures of merit, propagation conditions, and target depths and aspects. The dashed line is the locus of perfect agreement. The open triangle for the SQS-4 and the closed triangle for the Triband system do not correspond to the same environmental conditions.

The Operational Development Force has published operational evaluation data<sup>4</sup> for the 14-kc SQS-4 sonar system as installed aboard the WITEK in 1953. In Fig. 5, the points shown for probability of detection were obtained by dividing the number of successful parallel sweeps at a given range and target depth by the total number of runs at that range. The USL prediction method has been used to compute lateral range curves for comparison with the measured points. Two groups of points were plotted by OpDevFor. One group was described as taken under mixed-layer conditions with the target above the thermocline. The other group was obtained for a target in a moderate thermocline.

Upon examination of the original data, typical figures were derived for the environmental conditions and target depths for each group of points. For one group a 70-foot isothermal layer and a 50-foot or periscope-depth target seemed appropriate. For the other group, a 50-foot isothermal layer and a 200-foot target appeared to be the typical figures. The theoretical curves and measured points are in agreement if the figure of merit used is the alerted value of 165 db instead of the unalerted value of 147 db. Information received indicates that under the conditions of the repetitive lateral range runs, awareness of the target bearing is to be expected.

Figure 6 compares predicted and measured performance and consists of data obtained on the very recent anti-submarine warfare development exercise, AsDevEx-1. In this exercise, a convoy escort screen was composed of a 10-kc SQS-5 sonar aboard the WITEK, a 14-kc SQS-4 sonar aboard the KRAUS, a 24-kc SQS-1 sonar aboard the WILKE, a 25.4-kc SQS-11 aboard the NAWMAN and the O'BRIEN, and a 25.5-kc QHBa aboard the GREENWOOD and the COOLBAUGH. The ships were under the command of CAPT S. D. B. Merrill, who furnished the range-performance data and the associated BT information. The submarine target aspects were obtained from range recorder traces. The target depths are not known at this time. However, the pairs of points shown in Fig. 6 at a given range are plotted for each system for periscope-depth and 200-foot targets. Two general types of environmental con-

<sup>4</sup> See Evaluation of the AN/SQS-4 Sonar, final report on Project OP/S269/568, prepared and submitted by Commander Operational Development Force, 7 December 1953 (CONFIDENTIAL).

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Table 3

EXPECTED RANGES (KYD) OF ECHO-RANGING SONAR EQUIPMENTS (Submarine Target at Random Aspect)						
System	Frequency (kc)	Figure of Merit (db)	Hull-Mounted		VDS (125 ft)	
			Shallow Target (kyd)	Deep Target (kyd)	Shallow Target (kyd)	Deep Target (kyd)
QHBA Standard	25.5	131	1.7	1.3	2.3	1.7
	Tri-Beam	151	2.8	2.0	3.2	2.4
SQS-11	25.5	135	2.6	1.5	2.4	1.8
SQS-1	24.0	142	2.2	1.8	2.7	2.0
	20.0	142	3.0	2.2	3.2	2.4
SQS-4	14.0	147	4.1	2.8	4.6	3.4
SQS-5	10.0	147	5.0	3.0	5.7	3.9

Conditions

Ship Speed: 15 kt      Layer Depth: 100 ft  
Water Temp: 50° F.      Sea State: 2

ditions were encountered, namely, 70-foot to 150-foot isothermal layers and 0- to 30-foot layers. It may be seen that the lower frequency systems have a tremendous range advantage in the deeper isothermal layers. Under negative-gradient and shallow-layer conditions, where downward bending of rays is important, both types of systems seem to perform equally well with respect to range performance.

In order to compare system performance, the prediction technique may be used to compute expected ranges for all the sonars under the same hypothetical environment. For this purpose, a 100-foot isothermal layer with 50° F. water and Sea State 2 have been considered. In addition, 10 db were added to the figure of merit of a hull-mounted sonar to provide an estimate of the figure of merit of an equivalent sonar at 125-foot depth. The improvement in range shown in Table 3 for the deep sonar is due to an improvement in noise level rather than propagation loss. The figures of merit for the hull-mounted sonars are also shown in Table 3. It should be noted that the same figure of merit at different frequencies results in a range

advantage at the lower frequencies. For this purpose the data for the 10- and 14-kc systems and the 20- and 24-kc systems should be examined. A range advantage of approximately 2 to 1 can be realized by an equipment at 10 kc over one at 25 kc with the same figure of merit.

In conclusion, figure-of-merit measurements, target-strength data, and the Project AMOS propagation analyses appear to be valid in predicting ranges for sonars under various conditions. Predicted and measured ranges have been shown to compare favorably. When such ranges are computed, it is found that for different systems under the same environmental conditions, a 10-kc system can achieve approximately twice the range of a 25-kc system having the same figure of merit.

It is of interest to note that lateral range curves computed by means of the USL prediction technique played an important role in the recent AsDevEx-1 exercise. Using these curves as a basis for convoy-escort screen design, CAPT Merrill achieved an unusual record of submarine detections, i.e., at least 75 per cent of the opportunities, subject to the umpire's final decision.

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## STUDY G

### EXPECTED OPERATIONAL PERFORMANCE OF ECHO-RANGING SONARS AT 8 KC AND 14 KC

by  
M. Schulkin and M. R. Powers

#### INTRODUCTION

This analysis concerns the prediction of expected ranges for 8-kc and 14-kc, hull-mounted, echo-ranging sonars. Such sonars are currently being installed aboard Fleet destroyers under the SQS-4 series. Range performance calculations have been carried out for four figures of merit (140 db, 150 db, 160 db, and 170 db). The equipment figure of merit of an echo-ranging sonar is defined as the difference between the source level and the minimum detectable echo level.

Previously, a similar analysis of AMOS propagation-loss data was applied at 5 kc and 10 kc for various BT code classes for three submarine operational depth intervals.<sup>1</sup> Since that time a more complete and more detailed study of underwater sound propagation has been completed.<sup>2</sup> Since the date of the original report, there has also been a more specific requirement for information on expected range performance in the 8- to 14-kc region for the SQS-4 sonar. The present study supersedes the information previously reported. In particular, bottom reflection paths have been found to be less important than was thought to be the case.

#### COMPUTATION OF PROBABILITY OF DETECTION

Probability of detection was computed for a hull-mounted sonar for layer depths of 16, 64, 196, and 625 feet for the average surface temperature for each of four months of the year in the region 30° N to 40° N latitude. These probabilities were computed for shallow (49 feet) and deep (484 feet) submarine targets. The probability of detection is defined as the percentage of time that the echo-

signal excess is greater than or equal to zero. The computation of the echo-signal excess distribution requires a knowledge of the statistics for propagation loss, submarine target strength, and equipment figure of merit.

The present computations are based on the analysis of AMOS propagation data and dependence on layer depth, temperature, sea state, projector depth, receiver depth, range, frequency, and water depth. In addition, empirical bottom-loss data were used, together with a model of specular reflection paths, in order to compute the expected propagation loss for this mode of propagation.

The median target strength for a submarine at random aspect was taken as 14 db, a value which is in agreement with the present knowledge of submarine target strengths at 10 kc and 25 kc. This figure of merit was considered to be a parameter in computing expected range curves. Four different values, namely 140 db, 150 db, 160 db, and 170 db, were used. On the basis of previous experience with similar operational analyses of QHBs and SQS-4 echo-ranging sonars, 12 db was taken as the expected over-all standard deviation, and the signal excess was considered to be normally distributed.

Sample curves of resulting probability of detection versus range are shown in Fig. 1 for 8 kc and in Fig. 2 for 14 kc for the shallow submarine operating depth and for figures of merit of 140 db and 170 db. At these frequencies, it may be seen that bottom-reflected echoes may become important for negative sound-velocity-gradient conditions, especially when equipment with a figure of merit of 170 db or greater is used. A water depth of 2000 fm and an average temperature of 38° F. over the depth of the ocean were used in these computations.

<sup>1</sup>See Appendix B, USL Report No. 188.

<sup>2</sup>See Study A of this report.

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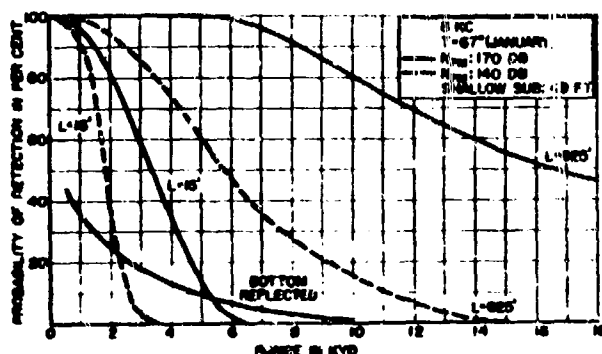


Fig. 1 - Probability of Detection vs. Range for 8-kc Echo-Ranging Systems

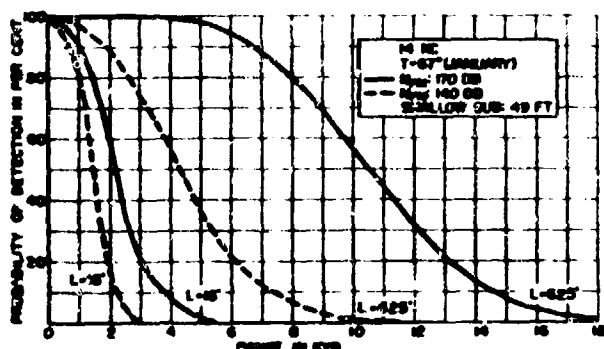


Fig. 2 - Probability of Detection vs. Range for 14-kc Echo-Ranging Systems

### ENVIRONMENTAL STATISTICS OF ATLANTIC OCEAN AREA, 30° N TO 40° N

A compilation of the monthly frequency of occurrence of various layer depths, sea states, and temperatures for the North Atlantic Ocean region

30° N to 40° N beyond the 100-fathom line was made. About one-third of the cards in the USL North Atlantic Environmental Data IBM Card File fall in this region. This compilation could then be considered a representative sampling of the operational environment within which equipments under evaluation are expected to perform. A tabular summary of these statistics is given in Table 1.

### EXPECTED RANGE AS AN OPERATIONAL SONAR PARAMETER

Computations of probability of detection were made for fixed ranges of 3, 6, 12, and 18 kyd for each of the classifications considered. For the purpose of classification, 0- to 36-foot layer depths were assigned a value of 16 feet for computation of probability of detection; 36- to 144-foot layer depths, the 64-foot value; 144- to 324-foot layer depths, the 196-foot value; and greater than 324-foot layer depths, the 625-foot value. The expected probability of detection was then obtained for each of the four typical months of the year by weighting the probabilities in each class by the frequency of occurrence in this class. Whenever the probability of detection for the bottom reflection path exceeded that of the direct path for any class, its value was used and weighted by the frequency of occurrence of that environmental class.

The expected range was then obtained as that range corresponding to at least 50 per cent weighted probability of detection. This was done for each month for acoustic frequencies of 8 and 14 kc, for figures of merit of 140, 150, 160, and 170 db, and for shallow and deep operational submarine depth

Table 1

STATISTICS OF ENVIRONMENTAL CONDITIONS, NORTH ATLANTIC AREA, 30° N TO 40° N								
Layer Depth (ft)	January		April		July		October	
	Sea State		Sea State		Sea State		Sea State	
	0-2	≥3	0-2	≥3	0-2	≥3	0-2	≥3
0-36	170	111	473	116	1523	314	323	126
>36-144	88	55	320	117	1085	486	198	110
>144-324	489	451	489	375	161	210	1109	1207
>324	666	510	265	171	1	2	16	30
	1413	1127	1555	829	2769	940	1646	1543
Mid-Water Surface Temperature	67° F.		65° F.		76° F.		75° F.	

Note: The numbers in the boxes refer to frequency of occurrence.

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classes. The monthly values of expected range were then plotted as shown in Figs. 3 through 6.

#### DISCUSSION OF EXPECTED SONAR PERFORMANCE OF 8-KC AND 14 KC SYSTEMS

In Figs. 3 through 6, the expected range is seen to have a minimum in July and a maximum in December and January. This behavior reflects the large number of negative temperature-gradient and shallow isothermal-layer patterns in the summertime

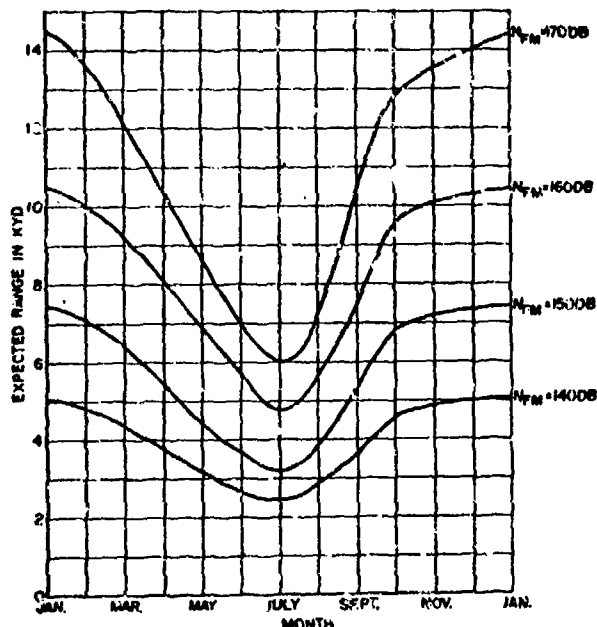


Fig. 3 - Monthly Expected Range of Detection of Shallow Submarines (49') at 8 kc in the North Atlantic Area, 30° N to 40° N

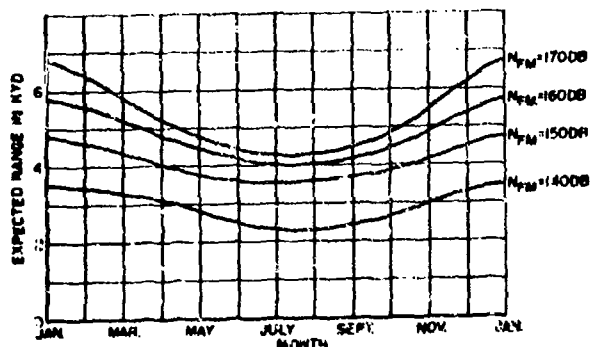


Fig. 4 - Monthly Expected Range of Detection of Deep Submarines (484') at 8 kc in the North Atlantic Area, 30° N to 40° N

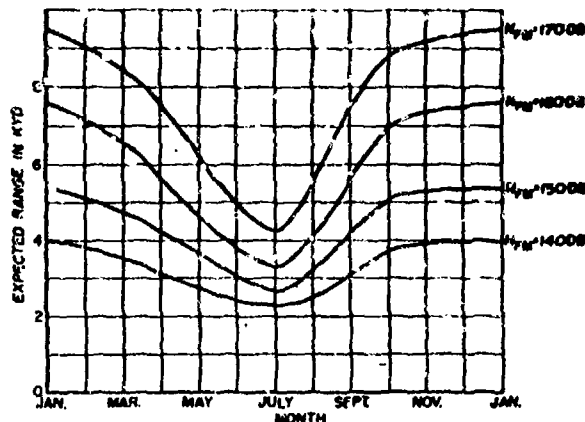


Fig. 5 - Monthly Expected Range of Detection of Shallow Submarines (49') at 14 kc in the North Atlantic Area, 30° N to 40° N

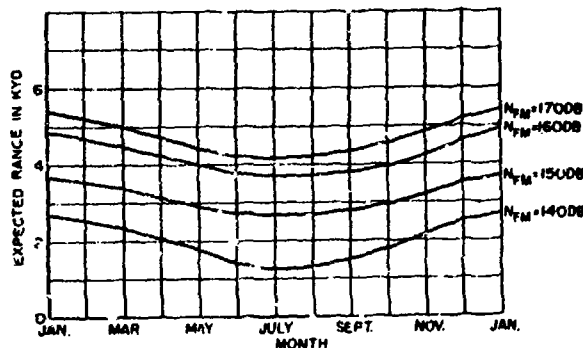


Fig. 6 - Monthly Expected Range of Detection of Deep Submarines (484') at 14 kc in the North Atlantic Area, 30° N to 40° N

and the large number of deep isothermal layers in the winter.

The effect of submarine operational depth is such that expected ranges for shallow submarines have greater yearly excursions than those for the greater depths, for both the 8-kc and 14-kc data. In winter, the deep submarines are less apt to be detected by hull-mounted sonars than are the shallow submarines. In summer, the situation is not quite so clear-cut.

In general, operational ranges improve with increase in figure of merit. However, the improvement is most noticeable against shallow submarines in the winter.

The effect of acoustic frequency on performance may be seen from the charts, which show that equipment with a figure of merit of 160 db at 8 kc has virtually the same performance as equipment with a figure of merit of 170 db at 14 kc.

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## STUDY H

THE USE OF RAY METHODS AND FIRST-ORDER DIFFRACTION CORRECTIONS<sup>1</sup>

by

H. W. Marsh, Jr.

## INTRODUCTION

In many wave problems, ray methods are convenient and accurate. Exact in the limit of high frequency, and employing simple formulas, these methods lose utility at low frequencies or because of inadequate numerical schemes for interpreting them. We shall give correction terms which permit an extension of ray methods to lower frequencies (and at the same time provide an evaluation of the validity of the high-frequency limit), and also set forth some useful formulas and numerical schemes for ray tracing and the quantitative evaluation of refraction (spreading) and interference.<sup>2</sup>

FOCUSULATION OF  
THE RAY AND WAVE THEORIES

Throughout we consider an inhomogeneous medium in which the phase velocity varies in one direction only. With respect to a given Cartesian frame, let  $c_0$  be the phase velocity at the origin and  $c$  that at other points. Take  $c$  to be independent of  $x, y$  so that  $c = c(z)$ . Define the index of refraction to be

$$n = c/c_0. \quad (1)$$

For waves of angular frequency  $\omega$ , the wave number at the origin is  $k_0 (= \omega/c_0)$ , and the wave number at ray points is

$$k = \omega/c = k_0/n. \quad (2)$$

<sup>1</sup>This study originated originally as DCL Technical Memorandum No. 1406-61-34, 27 September 1961 (UNCLASSIFIED).

<sup>2</sup>Part of this material was considered by Norman A. Haskell in "Diffraction Effects in the Propagation of Compressional Waves in the Atmosphere," Geophysical Research Paper No. 3.

We shall characterize a field point  $P$  by its Cartesian coordinates  $(x, y, z)$ , or its cylindrical coordinates  $(r, \theta, z)$ , or its polar coordinates  $(R, \theta, \beta)$ . Our interest will be devoted to cases of symmetry about the  $z$  axis. In such cases, the wave potential (of simply harmonic waves) can be expressed<sup>3</sup> in terms of cylindrical waves:

$$\begin{aligned} \phi &= k_0 \int_0^\infty \tilde{P}(r_n) e^{-ik_0 \sqrt{1-n^2} z} J_0(k_0 r_n) dr_n \\ &= k_0 \int_0^\infty \tilde{P}(r_n) e^{-ik_0 \sqrt{1-n^2} z} dr_n. \end{aligned} \quad (3)$$

From the ray point of view, energy travels through the medium along paths described by the equation

$$dr/dz = n \cos \theta_0 / \sqrt{1 - n^2 \cos^2 \theta_0}. \quad (4)$$

Here  $\theta_0$  is the inclination of the ray at the origin. Then, if  $\theta$  is the inclination at any point on this ray, Snell's law is

$$\cos \theta = n \cos \theta_0. \quad (5)$$

Combining equations (4) and (5), we may write

$$r = \int_0^z \cos \theta d\zeta. \quad (6)$$

The travel time along this ray is

$$t = \int_0^z 1/c \sin \theta d\zeta. \quad (7)$$

which may also be written

<sup>3</sup>It may be related to the wave number  $k$  by the relation  $\tilde{P}(r_n) = \tilde{P}(k_0 r_n) / k_0$ , where  $\tilde{P}(k_0 r_n)$  is a non-dimensional wave function, satisfying  $[(d^2/dk^2) + k^2 - k_0^2] \tilde{P}(k_0 r_n) = 0$ .



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$$c_0 t = r \cos \theta_0 + \int_0^r (\sin \theta / u) dr. \quad (8)$$

We may interpret the progressive divergence of a ray bundle as a corresponding spreading of wave energy. Thus, for a simple source behaving like  $e^{-ik_0 r}/R$  near the origin, we have from this point of view

$$I^{-1} = - (r \tan \theta) dr/d\theta_0 \quad (9)$$

as the ratio of wave intensity at unit distance from the origin to the intensity at other points on the ray.

### ASYMPTOTIC DEVELOPMENT OF THE WAVE FIELD

Equation (9) will break down when  $I^{-1}/r^2$  is small. In order to investigate this situation, we may appeal to an asymptotic development of Equation (2). It is assumed that  $P(r)$  is but slowly varying. Considering an extension of the method of stationary phase, write

$$\begin{aligned} \phi(u) &= k_0 [u - v(u, x)] \\ &= \psi_0 + (u - u_0) \psi'_0 + (u - u_0)^2 \psi''_0/2 \\ &\quad + (u - u_0)^3 \psi'''_0/6 + \dots \end{aligned} \quad (10)$$

as the Taylor series for  $\phi(u)$  about the point  $u_0$ . Then

$$\begin{aligned} \psi_0 &= k_0 u_0 r - k_0 v_{00} \\ \psi'_0 &= k_0 r - k_0 v'_0, \\ \psi''_0 &= -k_0 v''_0, \\ \psi'''_0 &= -k_0 v'''_0. \end{aligned} \quad (11)$$

The stationary point  $u_0$  is the solution of the equation  $\psi'_0 = 0$ . Therefore,

$$r = v'_0. \quad (12)$$

Equation (12) is simply the equation of that ray for which  $u = \cos \theta_0$ . Now in Equations (11),  $r$  and  $x$  are fixed. If we write  $r'$  for  $dr/d \cos \theta_0$ , where  $r$  satisfies (12) and  $x$  is held constant, we then have

$$\begin{aligned} \psi_0 &= \omega t, \\ \psi'_0 &= 0, \\ \psi''_0 &= -kr', \\ \psi'''_0 &= -kr'', \end{aligned} \quad (13)$$

Here  $\psi_0/\omega$  turns out to be the travel time along the ray in question, and the "ray intensity," Eq. (9), is simply related to the rate of change of this time.

According to the method of stationary phase, we can now write

$$\begin{aligned} \phi &\sim \int_{\Gamma} e^{ik_0 \phi(u)} P(r \cos \theta_0) \\ &\quad \times \int_0^{\infty} e^{ik_0 u/2} [u^2 r' + (u^3/2) r''] du. \end{aligned} \quad (14)$$

The path of integration in Eq. (14) is to pass through the point  $u = 0$  and is to terminate at infinity in such a manner that the integral converges absolutely for general values of  $k_0 r'$  and  $k_0 r''$ . We shall presume that both these quantities have a small non-negative argument, with results for other values following by analytic continuations.

An appropriate path of integration is  $\Gamma$ , as illustrated in Fig. 1.

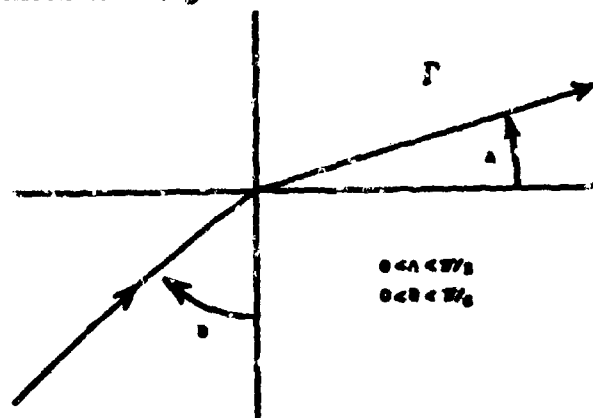


Fig. 1 - Path of integration,  $\Gamma$

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By a linear transformation of the variable of integration  $u$ , and an appeal to Cauchy's theorem, we get

$$\begin{aligned} \phi &\sim (2/h_0 r')^{1/2} h_0 F(r \cos \theta_0) \\ &\times e^{-i(\omega t + \pi/6 - h_0 r'^2/3r'^2)} \\ &\times \int e^{i\pi u + u^2/3} du, \end{aligned} \quad (15)$$

where

$$u = T^{1/2} e^{-2\pi i/3} (h_0 r')^2 / (h_0 r')^{1/2}, \quad (16)$$

and  $\Gamma'$  is as indicated in Fig. 2. The contour in Fig. 3 is equivalent to the contour in Fig. 2. By considering the contour in Fig. 3 and referring to the appropriate tables,<sup>4</sup> it is found that

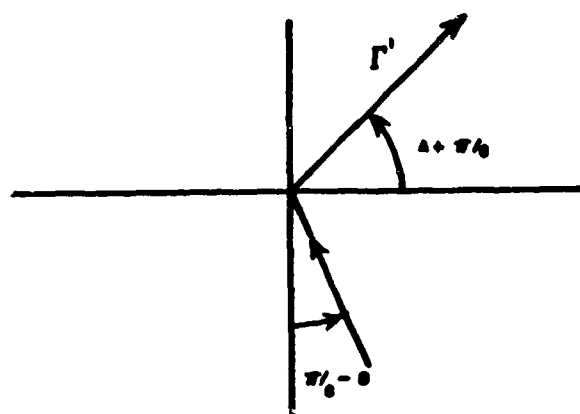


Fig. 2 - Transformed Path of Integration,  $\Gamma'$

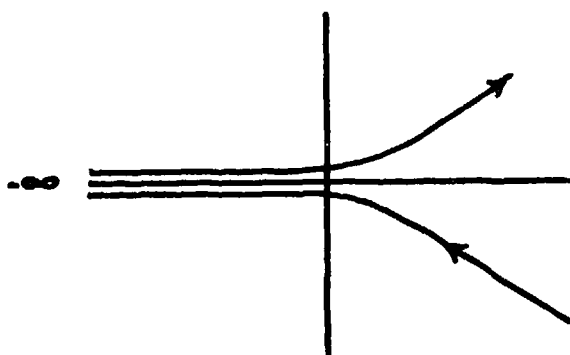


Fig. 3 - Equivalent Contour for Path of Integration,  $\Gamma'$

<sup>4</sup> Tables of the Modified Hankel Functions of Order One-Third, Computations Laboratory, Harvard University.

$$\begin{aligned} \phi &\sim (2/h_0 r')^{1/2} h_0 F(r \cos \theta_0) \\ &\times e^{-i(\omega t + \pi/6 - h_0 r'^2/3r'^2)} \\ &\times (\pi/12)^{1/6} b_2 [(h_0/2)^{2/3} r'^2/r'^{1/2}]. \end{aligned} \quad (17)$$

For large  $h_0$ , this is asymptotically

$$\phi \sim [h_0^{1/2}/(r')^{1/2}] F(r \cos \theta_0) (2\pi i)^{1/2} e^{-i\omega t}, \quad (18)$$

which is equivalent to Eq. (9), i.e., in the optical limit ( $h_0 \rightarrow \infty$ ). This method of stationary phase reduces to the geometrical, or ray, approximation. Let  $\phi_0$  denote this limiting form of  $\phi$ . Then we may write in general

$$\begin{aligned} \phi &= \phi_0 \frac{e^{i(h_0 r'^2/3r'^2 - 5\pi/12) \pi^{1/2} (h_0 r')^{1/2}}}{2^{1/2} 3^{1/6} (h_0 r')^{1/2}} \\ &\times b_2 [(h_0/2)^{2/3} r'^2/r'^{1/2}], \end{aligned} \quad (19)$$

or writing

$$a = h_0 r'^2/2r'^2, \quad (20)$$

and

$$\phi = \phi_0 J(a), \quad (21)$$

we have

$$\begin{aligned} J(a) &= e^{i(2a/3 - 5\pi/12) \pi^{1/2} 3^{1/6}} \\ &\times \pi^{1/2} a^{1/6} b_2 [a^{2/3}]. \end{aligned} \quad (22)$$

For  $a \rightarrow \infty$ , implying high frequencies,  $J(a) \rightarrow 1$ . Conversely, for  $a \rightarrow 0$ , implying low frequencies, or near caustic lines,

$$J(a) \rightarrow 2\pi^{1/2} e^{i\pi/12} a^{1/6}/3^{1/2} \Gamma(2/3), \quad (23)$$

and taking into account Eq. (9),  $\phi$  in this limit is

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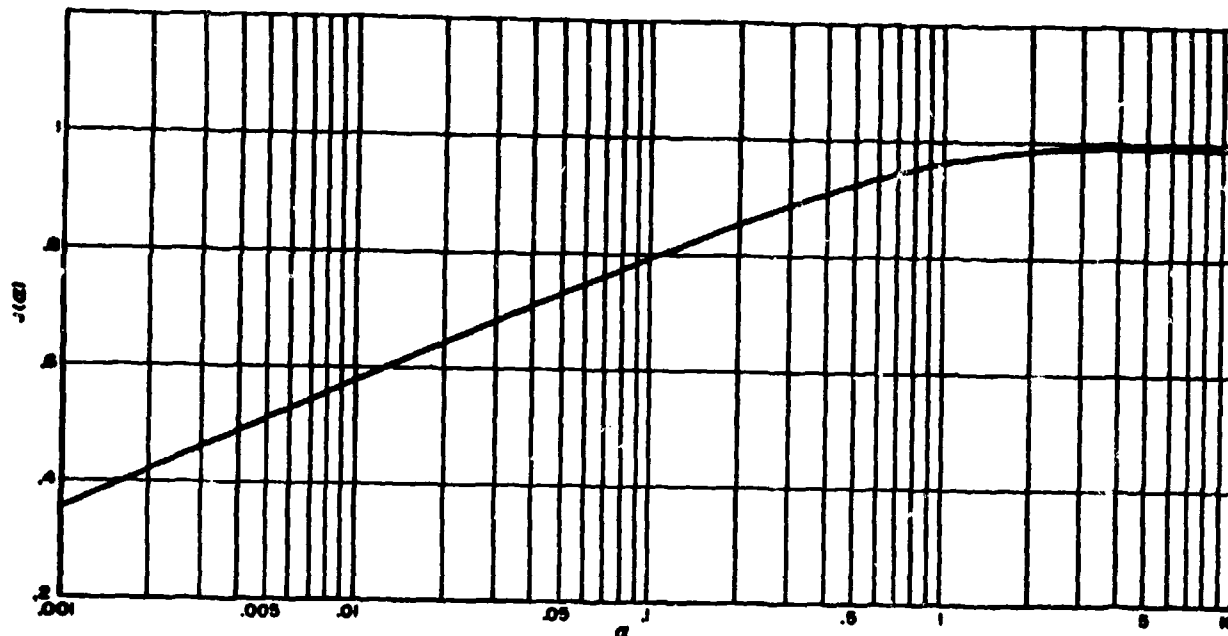


Fig. 4 - First-Order Diffraction Correction

$$\phi = 2^{1/6} \pi^{1/2} e^{\pi i/12} 3^{2/3} \Gamma(2/3) \times [h_0^{1/6} / (r'')^{1/3}] (\sin \theta_0 / m \tan \theta)^{1/2}. \quad (24)$$

A graph of  $f(\alpha)$  is given in Fig. 4. It is to be noted that  $f$  is indifferent to the sign of  $r''$  and that the conjugate value of  $f$  is to be employed when  $r'$  is negative.

#### A SIMPLE METHOD OF PREDICTING INTERFERENCE

The exact travel time along a single ray is seldom important. On the other hand, the difference of travel times along intersecting, and hence interfering, rays is often of interest. A significant feature of this interference is its change with distance. For example, the spacing between interference nulls is a most enlightening feature of the pattern.

Referring to Eq. (8), we have for constant  $x$ ,

$$dt/dr = (dt/d \cos \theta_0) d \cos \theta_0 / dr$$

$$\begin{aligned} &= 1/c_0 [(dr/d \cos \theta_0) \cos \theta_0 + r \\ &+ \int_{-x}^x n \cos \theta (d\theta/d \cos \theta_0) dx] \\ &\times d \cos \theta_0 / dr \\ &= \cos \theta_0 / c_0, \end{aligned} \quad (25)$$

where we have also used Eqs. (5) and (6). We then have

$$\begin{aligned} d^2 t / dr^2 &= -(\sin \theta_0 / c_0) d\theta_0 / dr \\ &= m \sin \theta_0 \tan \theta / c_0. \end{aligned} \quad (26)$$

Now, except near focusing regions,  $t \sim r^2$ , so that  $d^2 t / dr^2$  will normally be negligibly small. Thus, if  $\Delta t$  is the difference of travel times between rays with source inclinations  $\theta_0, \theta'_0$ , the change in  $\Delta t$  over a change  $\Delta r$  in distance will be nearly

$$(\Delta r / c_0) [\cos \theta_0 - \cos \theta'_0]. \quad (27)$$

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Therefore, the spacing between points of similar interference characteristics is nearly

$$(2\pi c_0)/\omega [\cos \theta_0 - \cos \theta'_0]. \quad (28)$$

This approximation is valid when  $l \sim r^2$  and when  $r \gg \Delta z$ . Its great utility comes from the fact that only the ray inclinations at the source need be known.

In cases where  $\theta_0$  and  $\theta'_0$  are nearly the same,  $\Delta t$  itself can be found simply. Consider the situation

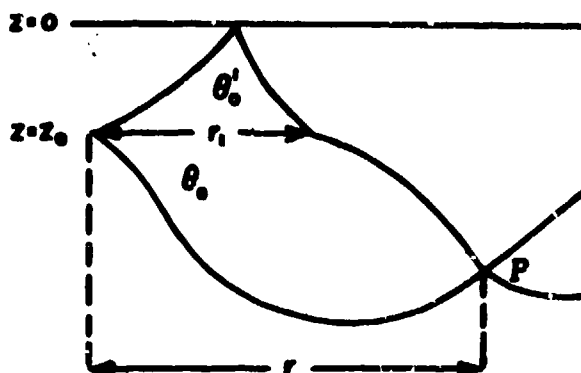


Fig. 5 - Two Ray Paths for Computation of Travel-Time Difference

illustrated in Fig. 5. The travel time difference, using Eq. (8), is

$$\begin{aligned} \Delta t = & r_1 \cos \theta'_0 / c_0 + (2/c_0) \int_{z_0}^{z_0} (\sin \theta' / n) d\zeta \\ & + (1/c_0) \int_{z_0}^{z_0} (\sin \theta' / n) d\zeta \\ & - (1/c_0) \int_{z_0}^{z_0} (\sin \theta / n) d\zeta + (r - r_1) \cos \theta'_0 / c_0 \\ & - r \cos \theta_0 / c_0. \end{aligned} \quad (29)$$

The first two terms represent the travel time  $t_1$  of the primed ray in the medium above the source. The remainder of  $\Delta t$  is the difference in time for two rays of inclination  $\theta_0$ ,  $\theta'_0$  traversing the same medium, to distances  $r$  and  $r - r_1$ , respectively. This remainder is nearly

$$(dt/d\theta_0)(\theta_0 - \theta'_0),$$

and the angular difference  $\theta_0 - \theta'_0$  is nearly

$$(d\theta_0/dr) r_1.$$

Hence,

$$\Delta t \sim t_1 + (r_1/c_0) dt/dr = t_1 + r_1 \cos \theta_0 / c_0. \quad (30)$$

Equation (30) is useful when  $\theta_0 - \theta'_0$  is small. When this is true,  $r_1$  can be computed using  $\theta_0$  in lieu of  $\theta'_0$ , so that the actual angle  $\theta'_0$  need never enter into the calculation. If greater accuracy is required, Eq. (30) can easily be extended to higher-order terms, which will involve, for example, the ray intensity and its rates of change. Therefore, the tracing of the basic rays, together with its first and second space or regular derivatives, will usually yield complete practical information on refraction (ray bending), diffraction, and interference.

## STRATIFIED MEDIA—SPECIAL CASES

In treating a problem involving an arbitrary index of refraction, it is usual to divide the medium up into strata, in each of which  $n$  varies in a simple manner. Ray tracing then consists of applying formulas to get the increments of distance, travel time, and intensity in each stratum, and proper combination of these to yield the properties of the entire ray. Thus, let  $x_i$  be the thickness of the  $i$ th stratum,  $r_i$  and  $t_i$  the increments of distance and travel time in the stratum, and  $\theta_i$  the angle at which the ray enters. Then

$$r = \sum r_i,$$

$$t = \sum t_i,$$

$$r^2 = - (r \sin \theta / \cos \theta_0) \sum (dr/d\theta_0).$$

Table 1 below gives formulas which apply to several forms of variation of  $n$ . In the table,  $c_i$  is the velocity at the point of entry of the ray, and  $n_i$  is  $c/c_i$ .

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Table 1

FORMULAS APPLICABLE TO VARIOUS RAY SHAPES			
$n$	$r_1$	$r_2$	Geometrical Form of Ray
$1 + g$	$z_1 \cot [(\theta_0 + \theta_1)/2]$	$(1/c_0) [\sinh^{-1} \tan \theta_1 - \sinh^{-1} \tan \theta_0]$	Circle
$1/\sqrt{1-(g/2)^2}$	$4/g \mu_1 \sin (\theta_1 - \theta_0)$	$(1/c_0) [r_1 \cos \theta_1 - 4 \sin^2 \theta_0 / 3g \mu_1 + 4 \sin^2 \theta_1 / 3g]$	Parabola
$2/\sqrt{1-g^2}$	$(\cos \theta_1 / g) \sinh^{-1} (g z_1 / \sin \theta_1)$	$(r_1 / 2g \cos \theta_1) [1 + \cos^2 \theta_1] + z_1 \sin \theta_1 / 2g \mu_1$	Sine Curve

### TABLES FOR RAY DIAGRAMS

A set of tables, which are useful in tracing rays through stratified media, in which the separate strata have constant velocity gradients, has been prepared on IBM equipment. These tables provide travel time, distance, and intensity increments. Entry into the tables is accomplished through the angle  $\theta_0$  of entry of the ray and the index of refraction  $n$ . Divided differences are provided. Linear interpolation, using these differences, will give sufficient accuracy for most purposes. The tables cover the ranges for  $\theta_0$  in degrees.

$$\theta_0 = \begin{Bmatrix} 1[0.1] 2 \\ 2[0.2] 5 \\ 5[0.5] 10 \end{Bmatrix} \times 10^m, m = -1, 0, 1$$

$$n = 1.00002 [0.00002] 1.002 \\ 1.002 [0.002] 1.01 \\ 1.01 [0.01] 1.1$$

to give the following tabulated quantities:

$$\theta_1 : \cos \theta_1 = n \cos \theta_0$$

$$\rho : \cot [(\theta_0 + \theta_1)/2]$$

$$\tau : (\sinh^{-1} \tan \theta_0 - \sinh^{-1} \tan \theta_1)/(n - 1)$$

$$\delta : \rho / \sin \theta_0 \sin \theta_1$$

Using these, and the notation of the preceding section, we have

$$r = \sum \rho_i x_i$$

$$t = (1/c_0) \sum \tau_i x_i$$

$$I^1 = (\sin \theta_0 \sin \theta_1 / \cos^2 \theta_0) \sum x_i \delta_i$$

These tables are available at the Laboratory either in tabulated form or on IBM cards.

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## STUDY I

AMOS LOW-FREQUENCY DATA-ANALYSIS METHODS<sup>1</sup>

by

T. P. Condon and J. F. Kelly

AMOS LOW-FREQUENCY  
DATA-ANALYSIS METHODS

## INTRODUCTION

One of the objectives of the AMOS low-frequency acoustic measurements is the determination of attenuation values in the frequency range from approximately 100 to 8000 cycles per second as a function of the mode of propagation. In pursuit of this objective, a total of 28 low-frequency acoustic stations were included during AMOS Cruises ELEVEN and TWELVE. The objectives of this report are to discuss a semiautomatic analysis system which was developed at the Underwater Sound Laboratory in order to process the data from these stations and to present sample plots which were made by the system and which point up one of the more important modes of propagation.

The data to be processed are in the form of broad-band dual-channel magnetic-tape recordings made at sea by the listening AMOS ship while the transmitting ship operated an underwater siren or MP-4(v) hammerbox and opened range to 80 kilometers. Each tape-recorder channel recorded the output of a hydrophone suspended at a depth of either 20 or 300 feet continuously while the range was being opened.

<sup>1</sup> This study appeared originally as UEL Research Report No. 219, 25 January 1954 (CONFIDENTIAL).

## METHOD OF ANALYSIS

A block diagram of the analysis system appears in Fig. 1. The purpose of the system is to resolve the broad-band signal into 10 narrow bands and to produce a plot of sound-pressure level as a function of the logarithm of the range for each band. In operation, the signal is fed from the magnetic tape to ten filters and then is averaged for three seconds in the rectifier averagers. The averaged output of each filter is then fed to one position of a Bell Telephone stepping switch, which is driven at such a rate that a given filter output is sampled once every 30 seconds. This is equivalent to a range increment of 150 to 250 yards, depending upon the speed of the transmitting ship. The signal for each filter is then fed to a Western Electric 4A Graphic Level Recorder, where a photoelectric reading head attached to the recorder shaft converts the voltages to a discrete number of pulses, which are fed to a binary counter and finally to an IBM Summary Punch. Thus, the averaged output of each filter is punched into an IBM card as the stepping switch rotates. After the cards are processed, they are fed to an X-Y Plotter, and the end result is a plot of sound-pressure level in decibels relative to one dyne per centimeter squared as a function of the logarithm of the range for each of the ten frequency bands. Most of the 28 stations taken to date have been processed by the system.

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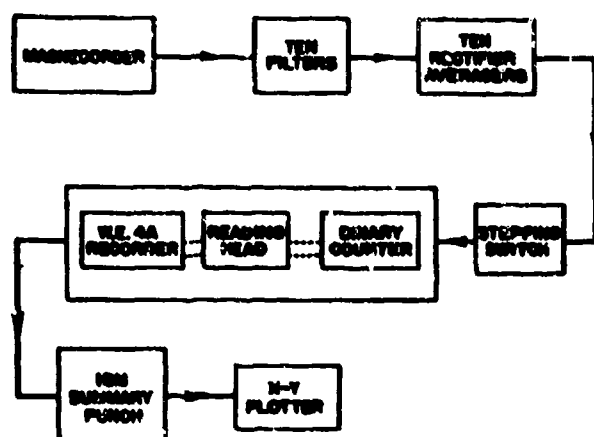


Fig. 1 - Block Diagram of Broad-Band Analysis System

### RESULTS OF ANALYSIS

In order to indicate some of the general results of the analysis made to date, propagation curves for three stations made at fairly widely separated locations in the North Atlantic Ocean will be presented. The mode of propagation best emphasized by these curves is that responsible for the foci

which occur at 70-kiloyard intervals in the southern portions of the North Atlantic and Pacific Oceans and at shorter ranges in more northerly latitudes. The curves are presented primarily to show the variation of range to the focus with geographical location and the variation in signal increase at the focus with frequency.

In Fig. 2 are shown the sound-velocity-depth profile and a propagation plot for a station taken at 68° north latitude and 01° west longitude in August. Ray calculations indicate that rays having an inclination of less than 0.5° from a source at a depth of 50 feet would be retained in the shallow surface layer. Those having inclinations between 0.5° and 10° would be refracted down into the layer between the bottom of the SOFAR channel (dashed line) and the ocean bottom and would return to a hydrophone at a depth of 50 feet at ranges of between 45 and 55 kiloyards; the focus peak would occur at 46 kiloyards. Rays with inclinations greater than 10° would reflect from the ocean bottom and would be received at all ranges between the source and 45 kiloyards. The agreement between the predicted and observed focus range for the frequency band centered at 3600 cps is good.

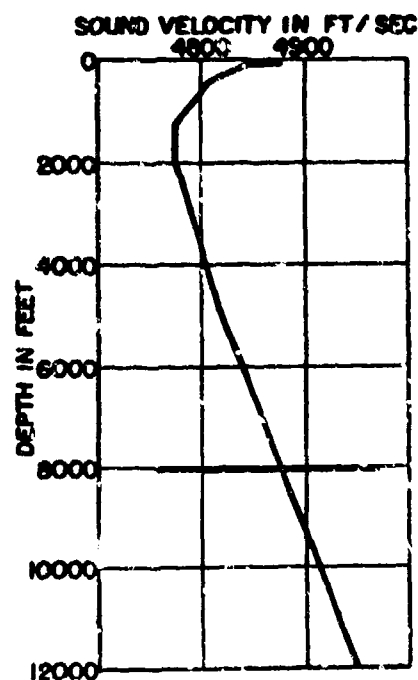


Fig. 2A - Sound-Velocity-Depth Profile

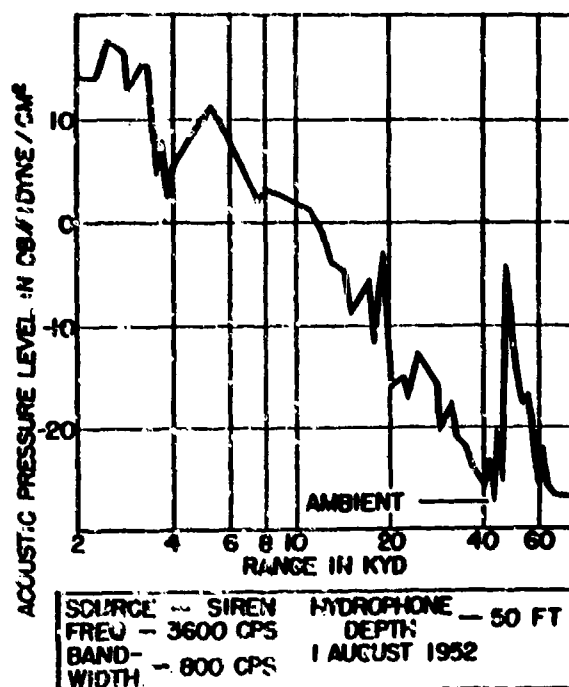


Fig. 2B - Propagation Curve

Fig. 2 - Data Obtained on Station 68° N, 01° W,  
1 August 1952

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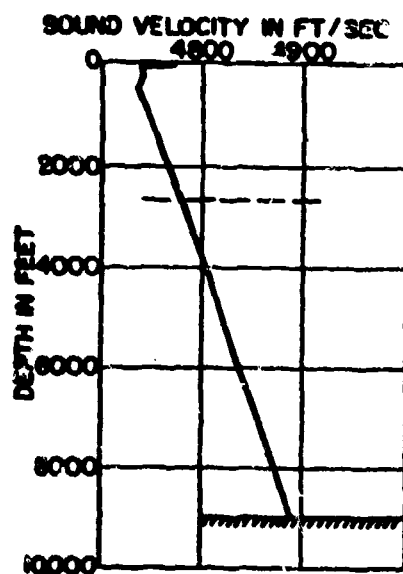


Fig. 3A - Sound Velocity-Depth Profile

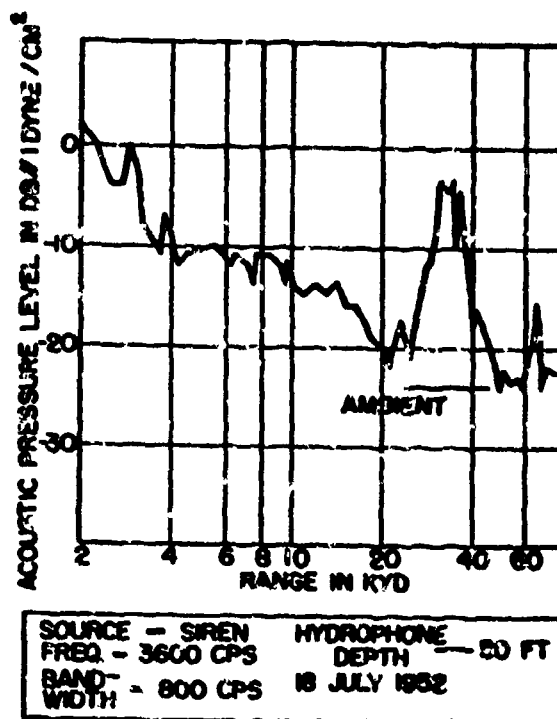


Fig. 3B - Propagation Curve

Fig. 3 - Data Obtained on Station 73° N, 61° E,  
18 July 1952

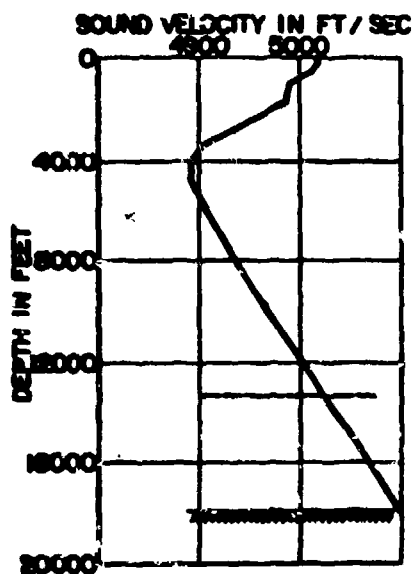


Fig. 4A - Sound Velocity-Depth Profile

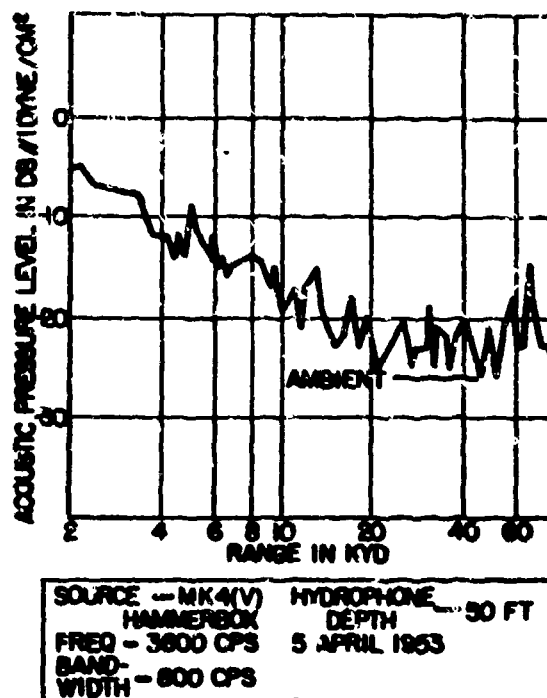


Fig. 4B - Propagation Curve

Fig. 4 - Data Obtained on Station 26° N, 78° W,  
5 April 1953

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Data for Fig. 3 were obtained on a station located 7° north of the previous one, at 75° north latitude and 01° east longitude during July. Ray calculations for this situation indicate that rays having inclinations of 1.1° to 12.5° at the source depth would refract back to a depth of 50 feet at ranges of between 27 and 46 kiloyards, and the predicted focus peak would be at 29 kiloyards. Here again, there is good agreement between the predicted focus at 29 kiloyards and the observed peak, which begins at 31 kiloyards.

Figure 4 contains data taken on a station well south of the other two, at 25° north latitude and 70° west longitude during April. The Mk 4(v) Hammerbox, which was used for this station, does not have so great an output as does the siren used on the previous two stations. In this instance, the predicted focus range is 70 kiloyards and the observed peak occurs at 69 kiloyards. Although this focus appears to be weaker than the other two, the total loss from 2 kiloyards to the focus is approximately 8 to 10 db less than in the previous two cases, and the apparent weakness is caused by a lower source output.

These three stations, for which focus peaks occurred at 48, 31, and 69 kiloyards, respectively, in the band from 3200 to 3800 cps, did not exhibit a marked focus at all frequencies. For purposes of comparison, the propagation plots presented in Figs. 2 through 4 are repeated in Figs. 5 through

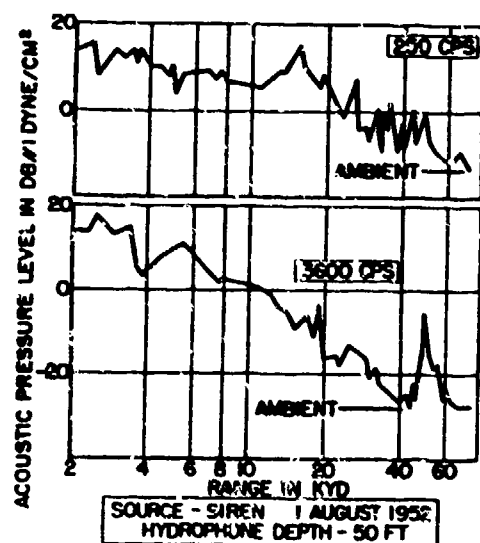


Fig. 5 - Comparison of Propagation Curves, 1 August 1952

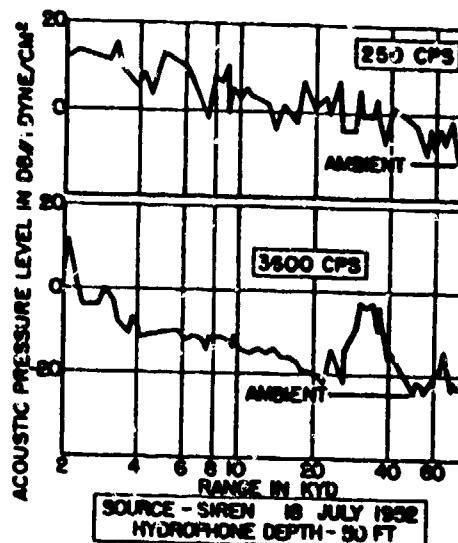


Fig. 6 - Comparison of Propagation Curves, 18 July 1952

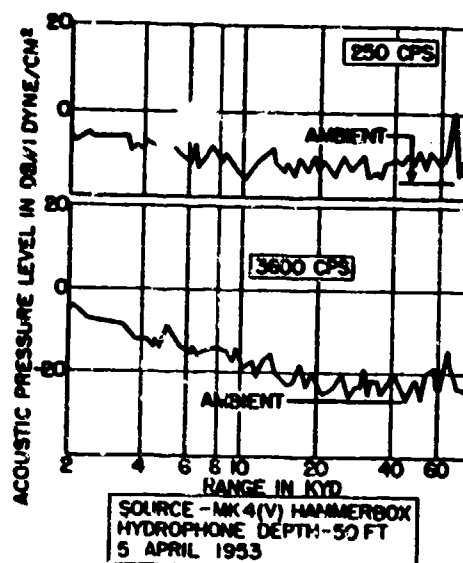


Fig. 7 - Comparison of Propagation Curves, 5 April 1953

7, accompanied by a plot for a 100-cps band centered at 250 cps.

Figure 5 represents the station where the focus was observed at 48 kiloyards. Although there is a rise in level of approximately 20 db for the band centered at 3600 cps, no marked level increase occurs at 250 cps. The same type of frequency behavior is observed for the second station, as is shown in Fig. 6. In Fig. 7, however, the rise at the focus is somewhat more pronounced at 250 cps than it is at 3600 cps.

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### CONCLUSIONS

No explanation for the dependence of focus intensity on frequency is offered at present, but it is interesting to note that the frequency band which best shows up a focus is not always the lowest one.<sup>2</sup> It is hoped that an analysis of explosive pulses used in conjunction with the siren and

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<sup>2</sup> These conclusions were appropriate when the original study was prepared. An explanation of this phenomenon is presented in Study J.

Mk 4(v) hammerbox during these experiments will shed some light on this behavior.

The AMOS low-frequency program has reached a stage where a substantial number of experimental stations have been occupied, and the data from most of these stations have been processed. The propagation curves are now being interpreted in the light of environmental factors. However, in order to obtain the statistical averages which will be required for a practical application of the data, a much larger number of additional stations will be required.

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## STUDY 3

COMPARISON OF COMPUTED AND MEASURED INTENSITIES  
FOR PROJECT AMOS NOISEMAKER MEASUREMENTS<sup>1</sup>

by

T. P. Condra, D. L. Cole, and J. F. Kelly

Theoretical intensity-versus-range plots have been computed for one set of Project AMOS deep-water, low-frequency measurements. The sound field in the vicinity of caustics and the bottom-reflected field are included in the computations. These plots are compared with actual propagation runs for which a broad-band noisemaker covering the frequency range from 250 to 8000 cps was used. The observed intensities are in substantial agreement with theory.

During the propagation program which the Underwater Sound Laboratory has conducted for several years in connection with Project AMOS, a variety of acoustic measurements have been made. Of these measurements, the type to be discussed in this study will be those in which a listening ship lay to in deep water while a transmitting ship operated a noisemaker and opened range to approximately 80,000 yards.<sup>2</sup> The object of this discussion is to present the method being used to interpret the propagation loss observed for each of ten frequency bands in the light of oceanographic factors.<sup>3</sup>

In general, three major modes of propagation are responsible for the behavior of the observed

signal versus range: (1) the direct sound field, which is always predominant at the short ranges; (2) the bottom-reflected field, which becomes predominant in the region beyond the direct field; and (3) the focused field, which is commonly observed at a range of about 60 kyd in the southern portions of the North Atlantic and Pacific Oceans and at shorter ranges in more northerly latitudes. For the direct and focused fields the major causes of signal reduction with range are spreading and absorption. For the bottom-reflected field, a boundary loss is introduced.

The first portion of this study will deal with the bottom-reflected field, and the final portion will be a discussion of the focused field. Since we are primarily interested in long-range propagation, it will suffice to state that the direct field terminates at a range of approximately 4 kyd for the station with which we are concerned. Measurements on this station were made by using an underwater siren in 1500-fathom water in the northern latitudes of the North Atlantic Ocean.

The expression for ratio of the intensity at one yard to that at any other in the medium (Eq. (9), Study H) may be written:

$$I^{-1} = (R \sin \theta / \cos \theta_0) dR/d\theta_0, \quad (1)$$

where

$\theta_0$  = the angle which the ray makes with the horizontal at the source,

$\theta$  = the angle which the ray makes with the horizontal at the receiver, and

$R$  = the horizontal distance from the source to the receiver.

It is customary to break the velocity-depth curve into layers of constant gradient, and then

<sup>1</sup> This study was delivered as a paper at the Ninth Navy Symposium on Underwater Acoustics, at the Naval Research Laboratory in June 1954 and was subsequently published in the January 1955 issue of the *Journal of Underwater Acoustics*.

<sup>2</sup> This type of run is designated as a "station" and will be referred to as such throughout this study.

<sup>3</sup> The method which was used to resolve these noisemaker runs into plots of signal level versus range for ten frequency bands was discussed in "AMOS Low-Frequency Data Analysis Method," by Thomas P. Condra and John F. Kelly, a paper delivered at the Eighth Navy Symposium on Underwater Acoustics, at the Underwater Sound Laboratory, 19-20 November 1953. See also Study I of the present report.

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$$R = \sum_{i=1}^N r_i$$

and

$$dR/d\theta_0 = \sum_{i=1}^N dr_i/d\theta_0$$

for  $N$  layers. The formulas which were used for computing  $r_i$  and  $dr_i/d\theta_0$  are as follows:

$$r_i = (c_0/g_i \cos \theta_0)(\sin \theta_i - \sin \theta_{i+1}); \quad (2)$$

$$(dr_i/d\theta_0) = (c_0 \sin \theta_0/g_i \cos^2 \theta_0) \times (1/\sin \theta_i - 1/\sin \theta_{i+1}). \quad (3)$$

In the layer containing a vertex, the range from the depth where the ray enters the layer to the curve depth on the other side of the vertex is

$$r_v = (2c_0/g_v \cos \theta_0) \sin \theta_v, \quad (4)$$

and the derivative is

$$dr_v/d\theta_0 = (2c_0/g_v \cos^2 \theta_0)(\sin \theta_v/\sin \theta_0). \quad (5)$$

In the above formulas  $g_i$  is the gradient in the  $i$ th layer,  $g_v$  is the gradient in the vertex layer,  $\theta_v$  is the angle which the ray makes with the horizontal at the depth where it enters the vertex layer, and  $\theta_i$  and  $\theta_{i+1}$  are the angles made by the ray upon entering and leaving the  $i$ th layer.

Thus, at any point after the vertex:

$$dR/d\theta_0 = (dr_v/d\theta_0) + \left[ \sum_{i=1}^{v-1} (dr_i/d\theta_0) - \sum_{i=v+1}^N (dr_i/d\theta_0) \right]. \quad (6)$$

The  $v-1$  and  $v+1$  refer to the layers just before and after the vertex layer, respectively. When the sum of the terms inside the brackets of Eq. (6) becomes equal to  $dr_v/d\theta_0$  in magnitude, then  $dR/d\theta_0$  vanishes (since all the  $dr_i/d\theta_0$  terms have the opposite sign from  $dr_v/d\theta_0$ ) and a caustic is reached. However, a second derivative exists unless it is also a cusp, in which case the third derivative would be required.

The corrected intensity in the vicinity of a caustic is obtained by multiplying the ray inten-

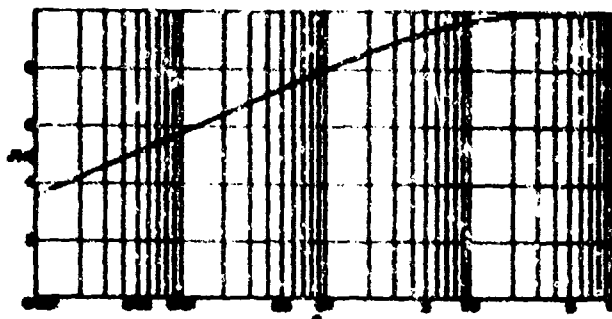


Fig. 1 - Diffraction Conversion Curve

sity by the square of a value obtained from Fig. 1. The value of the parameter is computed from the following relationship given in Eq. (20), Study 12:

$$u = h_0 (dR/dx)^3 / 2 (d^2R/dx^2)^2, \quad (7)$$

where  $x$  is  $\cos \theta_0$  and  $h_0$  is the wave number at the source.  $f(u)$  is given in Study 14.

The derivatives appearing in Eq. (7) were computed layer by layer as follows:

$$dr_i/dx = -(c_0/g_i \cos^2 \theta_0)(1/\sin \theta_i - 1/\sin \theta_{i+1})$$

$$= -(1/\sin \theta_0)(dr_i/d\theta_0),$$

$$dr_v/dx = -(2c_0/g_v \cos^2 \theta_0)(1/\sin \theta_v)$$

$$= -(1/\sin \theta_0)(dr_v/d\theta_0), \quad (8)$$

$$d^2r_i/dx^2 = (c_0/g_i \cos^3 \theta_0)$$

$$\times [(1/\sin^3 \theta_i - 1/\sin^3 \theta_{i+1})$$

$$- (3/\sin \theta_i - 3/\sin \theta_{i+1})],$$

$$d^2r_v/dx^2 = (c_0/g_v \cos^3 \theta_0)$$

$$\times (1/\sin^3 \theta_v - 3/\sin \theta_v). \quad (9)$$

For purposes of illustrating the method which was used to compute phase, two rays which reflect from the bottom will be considered with the source

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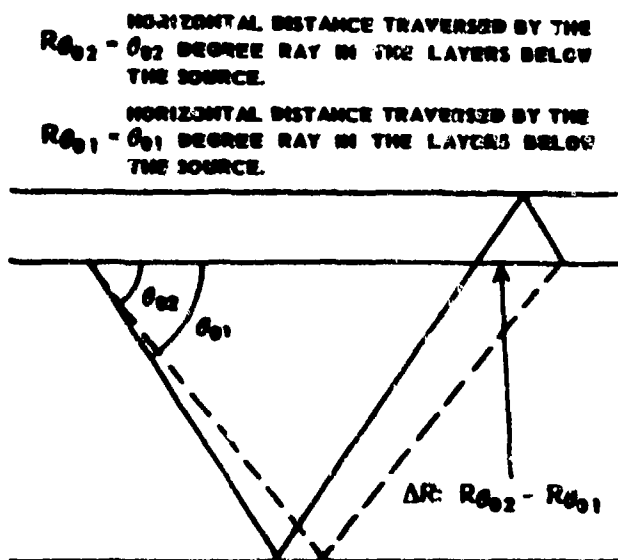


Fig. 2 - Geometry for Two Bottom-Reflected Rays

and the receiver at the same depth (see Fig. 2). The method applies, however, to rays with turning points and to cases where the source and the receiver are at different depths.

Assume that the range and its derivatives with respect to  $\theta_n$  have been calculated for the  $\theta_{n1}$  degree ray. The problem is to find the travel-time difference and, hence, the phase difference between the rays.

Break the travel-time differences into two parts, one part being the time taken by the  $\theta_{n1}$  degree ray to traverse the layer above the source and the other being the difference in travel time between the two rays in the layers below the source and the receiver.

$$R = \sum_{i=1}^N (c_i/g_i \cos \theta_i) (\sin \theta_i - \sin \theta_{i+1}) \quad (10)$$

$$T = \sum_{i=1}^N (1/g_i) \times (\tanh^{-1} \sin \theta_i - \tanh^{-1} \sin \theta_{i+1}) \quad (11)$$

$$dT/dR = (dT/d\theta_n) (d\theta_n/dR) = \cos \theta_n / c_n \quad (12)$$

Expand  $T$  in a Taylor series as a function of  $R$  (below the receiver).

$$T_{\theta_2} = T_{\theta_1} + (R_{\theta_2} - R_{\theta_1}) (dT/dR) + (R_{\theta_2} - R_{\theta_1})^2 / 2 (d^2T/dR^2) + \dots \quad (13)$$

$$T_{\theta_2} = T_{\theta_1} + (R_{\theta_2} - R_{\theta_1}) (dT/dR) + [(R_{\theta_2} - R_{\theta_1})^2 / 2] (d^2T/dR^2) + \dots \quad (14)$$

where

$$d^2T/dR^2 = -(\sin \theta_n / c_n) (d\theta_n/dR)$$

Equation (14) is the difference in travel time between the two rays in the layers below the source and the receiver, and this is an increase for the  $\theta_{n2}$  degree ray over the  $\theta_{n1}$  degree ray since  $dT/dR$  is always positive. In the layer above the receiver there is an increase in travel time for the  $\theta_{n1}$  degree ray over the  $\theta_{n2}$  degree ray. Thus, the total difference in travel time is

$$T_{\theta_1} - (T_{\theta_1} - T_{\theta_2}) = \Delta T,$$

where  $T_{\theta_1}$  is the travel time for the  $\theta_{n1}$  degree ray in the layer above the source.

It was found that for most cases the first term of the expansion was sufficient and that in the layers below the source and the receiver, the expression

$$T_{\theta_1} - T_{\theta_2} = \Delta R (\cos \theta_n / c_n)$$

was usually accurate.

Figure 3 shows theoretical plots of spreading loss versus range for signals reflected once from the bottom and for those reflected twice. The curves are based on intensities computed by using the formulas given above and the velocity-depth structure which existed at the time the measure-

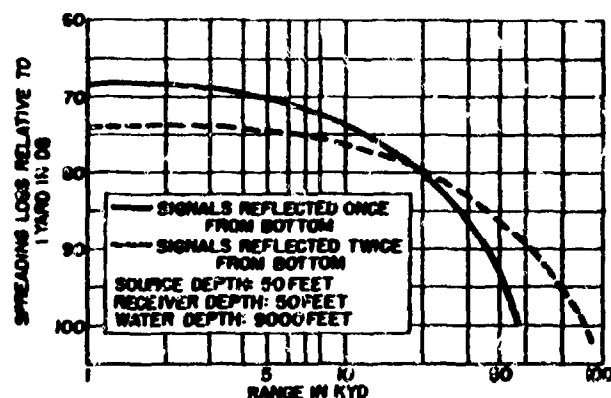


Fig. 3 - Theoretical Spreading-Loss Curves

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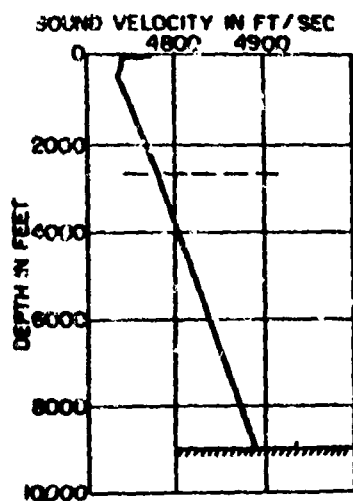


Fig. 4 - Sound-Velocity-Depth Profile

ments were made. The velocity-depth profile for these measurements is shown in Fig. 4. The station was made at 75° north latitude and 01° east longitude during July.

In a homogeneous medium the two curves would approach a slope of 6 db per distance doubled as the slant range approached the horizontal range. However, for the station under consideration and for most deep-water locations there is considerable curvature for rays which make small angles with the bottom. As a result of this curvature, the

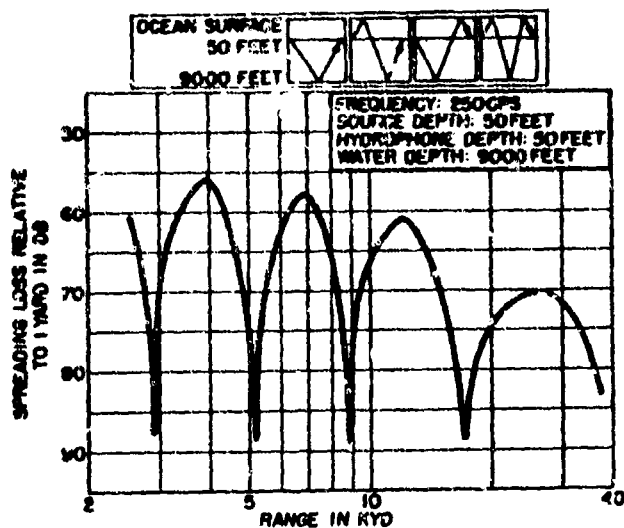


Fig. 5 - Spreading Loss for the Combined Four Signal Paths Reflected Once from the Bottom for a Frequency of 250 cps

rate of spreading loss is greater than 6 db at the longer ranges. For each of these orders of bottom reflection, as well as for all higher orders, there are four paths by which a signal can reach a receiver (see Fig. 5). For most of the ten bands into which the siren spectrum was resolved, the four signals could be combined simply by multiplying the intensity for one path by four. At the lower frequencies, however, the rate of change of phase with range was slow enough so that if phase were neglected, significant errors in the theoretical curve would result. The plot shown in Fig. 5 combines the four indicated paths for a frequency of 250 cps, which is the fundamental frequency of the siren used in the measurements. The source and the receiver are at depths of 50 feet, and the water depth is 9000 feet. Figure 6 presents a similar plot

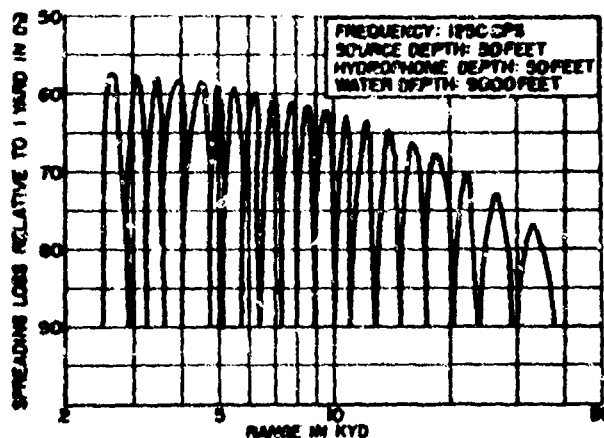


Fig. 6 - Spreading Loss for the Combined Four Signal Paths Reflected Once from the Bottom for a Frequency of 1250 cps

for the fifth harmonic of the siren. Because of the proximity of the peaks at this frequency and because there were two or more harmonics in the pass band of all the filters used in processing the data above the third harmonic, phase above this frequency was neglected.

The next step in the analysis was the construction of a theoretical curve which indicated loss versus range. The computations for this purpose included absorption and spreading for each of the ten frequency bands.<sup>4</sup> When the spreading loss

<sup>4</sup> Absorption was computed from Leonard's formula and by using the new constants which are presented by H. W. N. M. J. and Morris Scholkin in Study A of this report.

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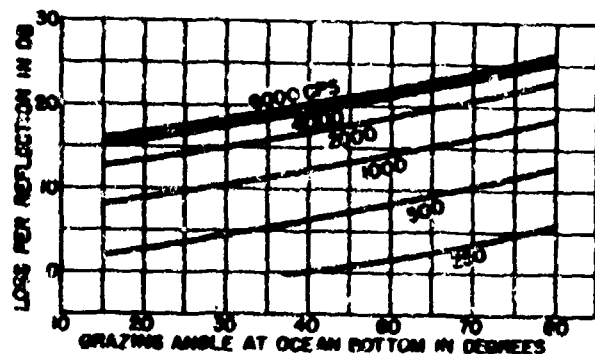


Fig. 7 - Reflection Loss vs. Grazing Angle of Ocean Bottom

and absorption had been established as functions of range, the theoretical plots for signals reflected once from the bottom were compared with the measured propagation plots at other ranges where spreading predicted that these signals would be much stronger than those of higher-order reflection. A smoothed curve of loss per reflection versus angle of reflection at the bottom was then constructed for each of the ten frequency bands and extrapolated to include angles from  $15^\circ$  to  $80^\circ$ . Some of these curves are shown in Fig. 7 and indicate that the reflection loss increases with frequency and angle of reflection. The maximum range used in determining the curves was 10 kyd, which corresponded to a reflection angle of  $30^\circ$  for this station. Values from these curves were used to correct signals of higher-order bottom reflection, and the various orders were combined. The end result was a predicted curve which included spreading, absorption, and boundary loss for each frequency band.

In order to check these results, the predicted curves of level versus range were compared with the observed plots with the view that any large error in bottom-reflection loss would show up beyond the 10-kyd range, the maximum range used in determining the curves in Fig. 6. The agreement between the predicted and observed levels was good except for the 250-cps plot. This plot indicated that the bottom-reflection loss is not zero for angles of less than  $37^\circ$  (see Fig. 8). In Fig. 8 the solid curve is the predicted one. It is evident from Fig. 7 that the decrease in observed signal is more rapid than that expected if the loss were zero for grazing angles of less than  $37^\circ$ . Points beyond 26 kyd have been omitted because focused rays which do not reflect from the bottom arrive in

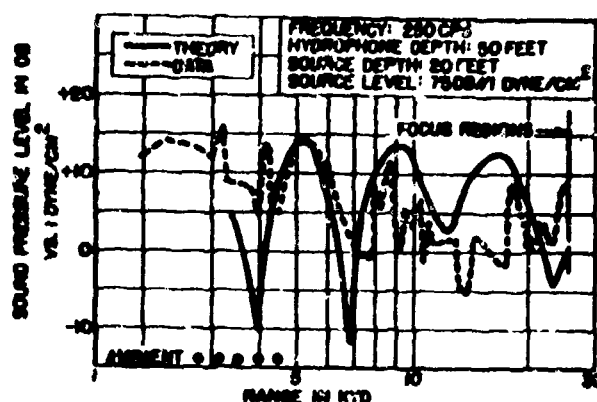


Fig. 8 - Sound Pressure Level vs. Range for a Frequency of 250 cps

this region. A sample of the good agreement at other frequencies is shown in Fig. 9, which is a plot of measured acoustic-pressure level versus range for the frequency band from 4000 to 5000 cps. The smooth curve is the one predicted on the basis of the bottom-reflection losses shown in Fig. 7.

Two focus regions, one at a range of 30 kyd and one at a range of 60 kyd, were observed during this station. These were caused by rays with initial source angles of less than approximately  $12^\circ$  which went through turning points at depths between 6000 and 9000 feet. As a result, four caustics were formed at shallow depths in both focus regions; each caustic was associated with one of the four possible paths. Because of the rapid convergence of the rays in the caustic region and the subsequent interference between neighboring rays, it was necessary to correct the levels based on

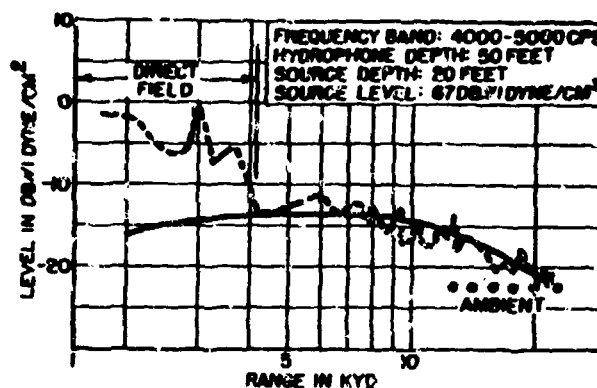


Fig. 9 - Sound Pressure Level vs. Range for the 4000- to 5000-cps Frequency Band

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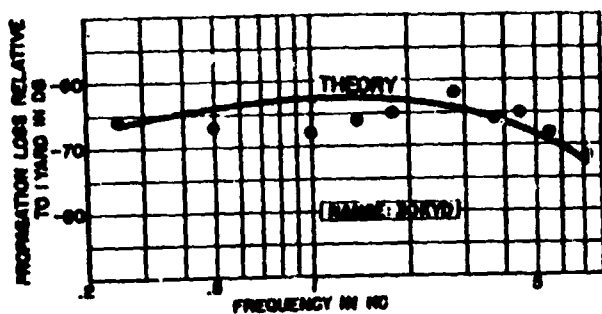


Fig. 10 - Measured Propagation Loss to First Focus Region

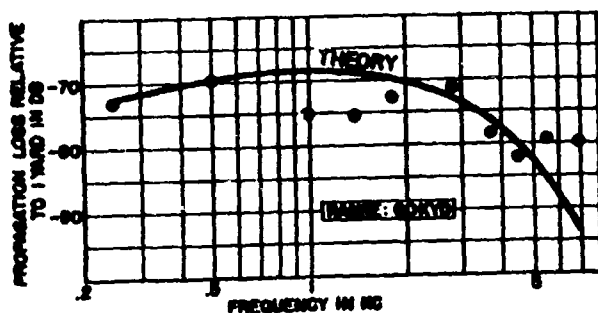


Fig. 11 - Measured Propagation Loss to Second Focus Region

ray geometry for diffraction. This correction was accomplished by using the formulas given previously.

Figure 1, which is a graph of the correction factor for diffraction, predicts that the maximum intensity does not occur at the caustic where the first derivative vanishes but at some nearby point, the position of which is dependent on frequency. This fact is in agreement with the findings of Airy. By means of these corrections and by application of absorption loss, a theoretical curve for minimum

propagation loss versus frequency for each focus region was drawn.

The curve for the first focus region near 30 kyd is shown in Fig. 10. This curve indicates a minimum loss of approximately 62db at a frequency of 1500 cps which is caused by less intense focusing at the lower frequencies and higher absorption at the upper frequencies. Since the ambient level is lower and the bottom-reflected field drops to the ambient more quickly at higher frequencies, there is an argument for choosing one of the higher frequencies when attempting to observe the focusing phenomenon.

The predicted and observed propagation losses for the second focus region near 60 kyd are shown in Fig. 11. Although some scatter is apparent, there is good general agreement between the predicted and observed values. The peak of the theoretical curve appears at approximately 1000 cps as opposed to 1500 cps in Fig. 10. This fact indicates that as the range to the focus region increases, absorption will cause the optimum focus to shift toward increasingly lower frequencies. The scatter in Figs. 10 and 11 may well be an error in source level.

In conclusion, the complete intensity profile for one of the AMOS low-frequency noisemaker runs has been calculated according to the oceanographic picture. It has been possible to calculate the peak intensity in the focus region within a few decibels of the observed intensity. Bottom-reflection losses have been obtained as a function of the angle of reflection at the bottom. It remains now to check whether the behavior of other AMOS stations is similar to the behavior of the station discussed in this paper. Future plans also include a comparison of the bottom-reflection losses for each station with bottom cores and seismic profiles made during the measurements.

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Research Report No. 265

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1 January 1963 - 31 December 1964), by H. Wynn  
March, H., and Morris-Schulkin. 31 March 1965.  
1-ix + 83 p.  
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The Project AMOS work which was carried out

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- I. Underwater sound transmission—
- Measurement
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